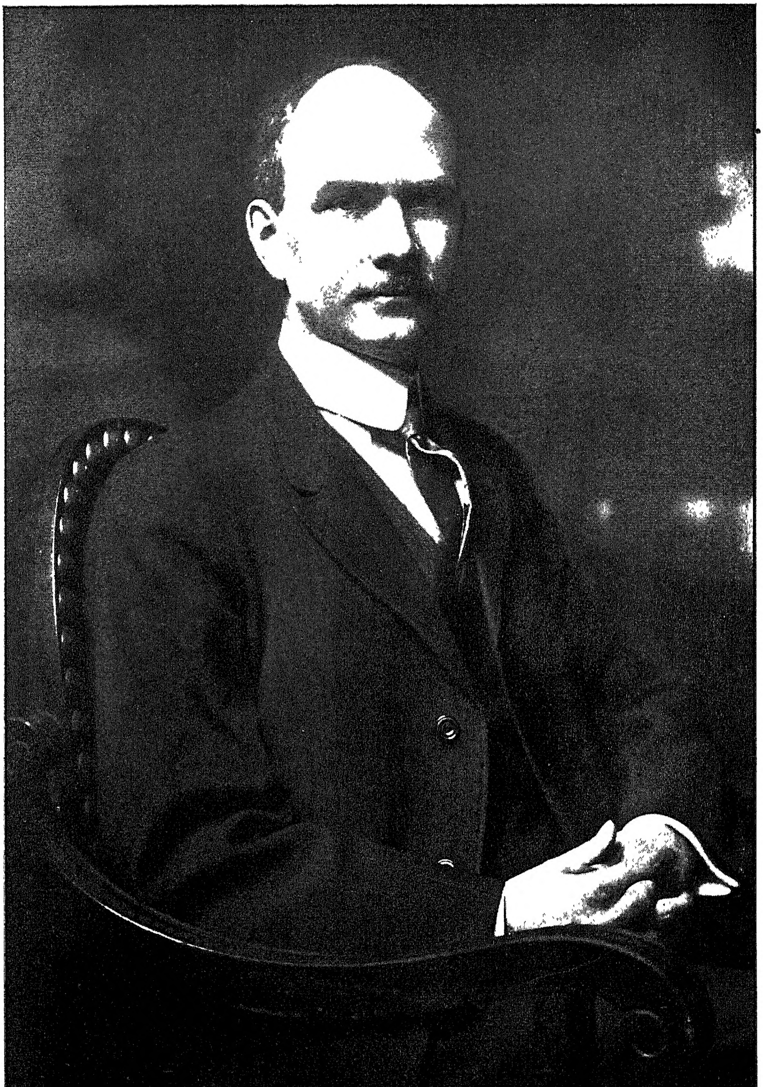

Dugald C. Jackson

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CONTENTS.

A paper presented at the 255th meeting of the American Institute of Electrical Engineers New York, January 13, 1911.

OPEN ATMOSPHERE AND DRY TRANSFORMER OIL AS HIGH-VOLTAGE INSULATORS†

BY HARRIS J. RYAN

I. CAUSE OF THE GREAT DIELECTRIC STRENGTH OF AIR FILMS ON THE SURFACE OF A CONDUCTOR AT HIGH-POTENTIAL

a. By the method that employs a conductor of circular section mounted in the air at the center of a hollow conducting cylinder, the electric stresses at the conductor surface required to start corona were observed and reported to the Institute.* These observations are recharted, using kilovolts per inch, in lieu of coulombs per inch-cube, for the stresses, so as to locate the single curve, drawn in Figs. 1*a* and 1*b*. These data apply to the normal indoor atmosphere at a temperature of 70 deg. fahr., barometer of 29.5 in. (750 mm.) and an elevation of 850 ft. (259 m.) above sea level. The galvanized sheet iron cylinder was new and clean, 3 ft. (91.4 cm.) long, 15 in. (38 cm.) diameter and *open at both ends*. Approximate sine-wave, 133-cycle, high-voltage alternating e.m.fs. applied the electric stresses between the conductors and the cylinder. The maximum values of these e.m.fs. were checked by needle spark-gaps. The conductors were clean brass rods for the *one quarter inch* (6.35 mm.) and larger diameters, and clean copper wires for the smaller diameters.‡ The work was done indoors and at night to facilitate visual observation of the *complete corona-start*. The size of the room employed was approximately 40 by 40 by 15 ft. (12.2 by 12.2 by 4.5 m.), and the air in it reasonably dust free due to ordinary

*The Conductivity of the Atmosphere at High Voltages, Harris J. Ryan. TRANSACTIONS A. I. E. E., Vol. XXI, p. 275, 1904.

†A paper submitted to the A. I. E. E. through the San Francisco Section, for the January 13, 1910 meeting at New York.

‡The term clean here means ordinarily clean and not "*clean*" a present day corona term.

settling. The ions and radioactivity present in the air were not observed because their existence and importance in corona formation were not understood at the time.

In the former paper it was shown that the relation of these surface stresses to the corresponding conductor diameters was such as to point strongly to the existence of a dielectrically stout thin film of air next to the conductor surfaces as suggested earlier by Steinmetz. The envelope method was employed to locate the distances from the surfaces of the conductor to the zone whereat the air behaved the weakest in relation to the diminishing radial stresses. For sizes above one-quarter inch this distance to the zone of supposed initial rupture was found to be

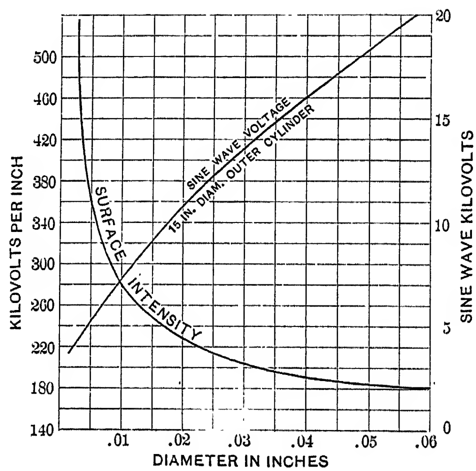


FIG. 1*a*

nearly uniform at about 0.07 in. (1.78 mm.); the corresponding rupturing stress was found to be 76 kilovolts per in., or 30 kilovolts per cm. The fact that in a particular case the corona starts with a definite minimum radial thickness and that this thickness ends at an outer radial stress of 76 kilovolts per in. was considered to be highly significant of the character of the strong air film; more especially so because this stress is the same as that required to rupture air in a uniform field between two parallel plate electrodes according to J. J. Thomson and other authorities on the conduction of electricity through gases. It indicated that initial corona is dependent not only on the application of a certain minimum stress but also upon a certain

minimum *striking distance* through which such stress must be applied. As the stress about the charged conductor is radial in direction its density diminishes as the distance from the surface increases. Within the zone 0.07 in. (1.78 mm.) from the surface of the conductor at which the corona forming critical stress is 76 kilovolts per in. the average stress is, therefore, higher. It appeared reasonable to expect if this *striking distance is* necessary that it would be shorter for smaller diameters and longer for the larger diameters, though the relation might not be one of direct proportion.

With the smaller diameters owing to the greater rate of spread of the stress as it extends from the surface of the conductor, the

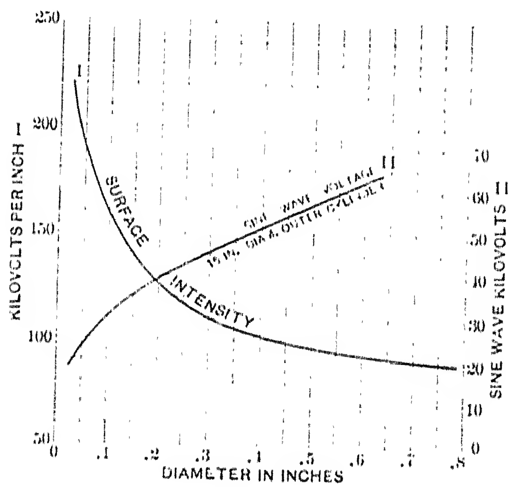


FIG. 1*b*

average stress applied between the surface of the conductor and the zone of critical stress, 76 kilovolts per in. would be greater, the *corona striking* effect would be greater, making it possible to start corona through a shorter minimum range of action. For the same reason larger diameters should employ somewhat greater striking distances. With the larger diameters, however, the spread of the stress is far more gradual which results in a relatively smaller increase in striking distance with increase in diameters. Below one-quarter inch the envelope method had given results that were anomalous. It now seemed reasonable to expect that these anomalies were due principally to the graphical errors that can hardly be avoided for the small di-

ameters, and that the coronas about such small diameters started in the same manner as in the case of the larger diameters, *viz.*, by a certain striking distance that terminates at the critical stress, 76 kilovolts per in.

It was evident, if this view is correct, that the critical stress zone, 76 kilovolt per in., should be found in each case at a certain distance from the conductor surface in initial corona formation, that in applying this test in Fig. 1, the striking distances for the various diameters should have a continuous relation and correspondingly locate a curve of striking distances and diameters that should have a rational character throughout the whole range of conductor sizes. The curve in Fig. 2 was thus located from the data curve in Fig. 1*a* and 1*b*.

In one respect the form of the curve in Fig. 2 is at first a surprise, that the striking distance should increase almost exactly

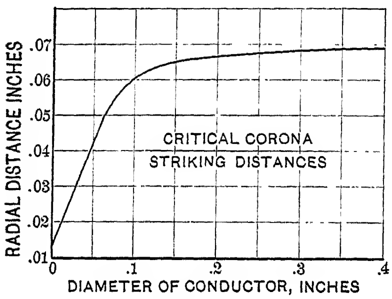


FIG. 2

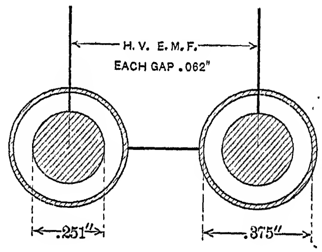


FIG. 3

in proportion to the diameter of the conductor from the smallest sizes to a diameter of about 0.075 in. (1.9 mm.); that immediately beyond this diameter and thereafter the striking distances increase very slowly with the diameter, attaining a value of 0.07 in. (1.78 mm.) at a diameter of 0.5 in. (12.7 mm.) and finally a value of about 0.25 in. (6.35 mm.) at a very great diameter. This sudden bend in the curve occurs at the diameter whereat the corona even under the influence of an ideally uniform radial electric field does not form uniformly; it starts in a patchy fashion. It has been observed that the factors that determine whether the corona will or will not start uniformly over the entire surface of the conductor are dependent upon:

1. The density of the gas, *i.e.*, upon its temperature and pressure.
2. Upon the degrees of uniformity of the electric stress producing the corona.

3. The spread of the electric stress in the air about the conductor and, therefore, upon the radius of curvature of the conductor.

These factors come into effect in such a manner for air at normal temperature and pressure when the striking distance attains a value of about 0.055 to 0.060 in. (1.39 to 1.52 mm.) for conductor diameters of 0.075 in. to 0.10 in. (1.9 to 2.5 mm.), such that thereafter the aggregate striking distances increase very slowly with increase in diameters. At these diameters above 0.10 in. (2.5 mm.) uniform corona never starts in air at normal density. It always makes an irregular start.

b. Experiments above, below, and at normal atmospheric pressure sustaining the view that corona and spark-discharges require certain critical striking distances in which to be established at minimum stress; below these distances the stresses required to produce coronas or spark-discharge are increased.

The relation in Fig. 2 of striking distances and diameters strongly indicated that corona for all cases is simply a spark-discharge phenomenon wherein the conductor is one electrode and the air conducting by *diffusion* is the other. Under these circumstances the spark itself must be spread out quite fully, completely resulting in a glow-discharge of the familiar corona. The first verification experiment was undertaken as follows:

Two pair of concentric clean brass cylinders were provided, electrically connected, and the normal air in the gaps between the cylinders stressed by the application of sine-wave alternating high voltage as indicated in Fig. 3. The diameters of the inner cylinders were 0.251 in. (6.35 mm.) and the internal diameters of the outer cylinders 0.375 in. (9.4 mm.), so that the radial depths of air between the conducting cylinders was 0.062 in. (1.5 mm.) which is nearly equal to the corresponding striking distance, 0.066 in. (1.67 mm.) given by the curve in Fig. 2 for a diameter of 0.251 in. (6.35 mm.). It was found in this experiment that the alternating voltages that produced a pair of sparks in series from cylinder to cylinder across the source terminals also produced a stress of 76 kilovolts per in. at the inner surfaces of the outer cylinders. One pair of cylinders was cut out and the high voltage applied to the remaining pair. It was then found that exactly *one-half* of the former voltage had to be applied to establish a single discharge between one pair of cylinders. The stress at the inner surface of the outer cylinder was 76 kilovolts per in. as before. Thus the identity of corona

and a spark discharge between conductors at corresponding electric stresses was established.

If the critical striking distance required for initial corona formation at minimum voltage is due to the *headway* requirements of *ionization by collision*, the variation of the pressure of the air in which the concentric cylinders are mounted should from general knowledge be equivalent to a certain corresponding variation of the length of the air gap between the cylinders. A pair of the above cylinders was placed under a large bell-jar

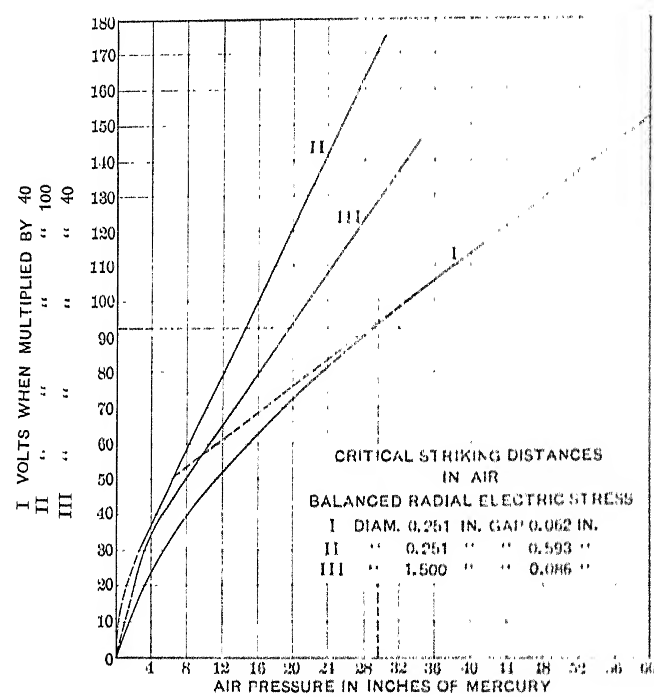


FIG. 4

of a laboratory air pump. The above experiment was repeated at various pneumatic pressures below and above that of the normal atmosphere. The relation obtained between the approximate sine-wave 60-cycle alternating voltage and the air pressure in inches of mercury at which the discharges occurred were used to locate curve *I* in Fig. 4. Below one atmosphere, 29.5 in. (750 mm.) of mercury, the relation is curvelinear and above that pressure, rectilinear. This result means that at one atmosphere the critical striking distance is just equal to the

depth of the air gap between the cylinders; above one atmosphere the critical striking distance is shorter and below one atmosphere it is longer than the air gap. When the critical striking distance is longer than the distance between the electrodes the critical stress zone, 76 kilovolts per in., falls beyond the inner surface of the outer cylinder, a higher average stress and, therefore, voltage, must be applied to make up for the lack of headway required to start the spark. Starting at a low value of air pressure, the voltage rises at a more rapidly diminishing rate than the air pressure because the shortage in headway required for sparking at minimum stress is constantly diminishing. At one atmosphere the shortage in required striking distance has just disappeared, and after that the air pressure and sparking voltage increase in direct proportion. It is obvious that when the shortage in striking distance disappears there should be a change in the relation of voltage to air pressure but it is not just yet obvious that it should be the law of direct proportion. We will return to a consideration of this later on. To check such an understanding of these matters further and to show that the striking distance just equaled the air gap at one atmosphere because it was chosen in conformity with the relation in Fig. 2, gaps were provided between two pairs of concentric cylinders having diameters differing from those employed above. Cross sections of these cylinders with their dimensions are given in Fig. 5. The experiment recorded in curve *I*, Fig. 4, was repeated with each of these pairs of concentric cylinders and the results located curves *II* and *III*, Fig. 4. In each of these cases the depth of air gaps were chosen so as not to conform with the striking distance and their corresponding conductor diameters found in Fig. 2. The changes from curve to right line in the sparking-voltage to air-pressure relations as found for these two cases occur at pressures differing from one another and from that of the normal atmosphere just as should be the case if the above view is correct.

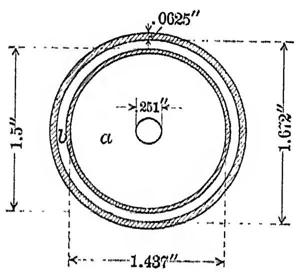


FIG. 5

The curves given in Fig. 4 have a bearing upon the manner in which corona forming voltage will vary with barometric pressure and, therefore, with altitude; this will be referred to later on.

*c. Confirmation results obtained by Baille, Paschen and Schuster**

Many years ago Baille and Paschen by means of continuous e.m.fs. observed with great care the voltages required to spark through various distances of normal indoor atmosphere between metal spheres of various diameters and between parallel metal plates. Later on Schuster calculated the corresponding electric stresses at the surface of the spherical and plane electrodes. His results stood originally in c.g.s. units. They have been re-expressed in kilovolts per in., for surface stress and inches for distance in Fig. 6.

We can readily make a mental picture of the electric fields between pairs of concentric cylinders, spheres and parallel planes. Invoking our judgment we can compare mentally

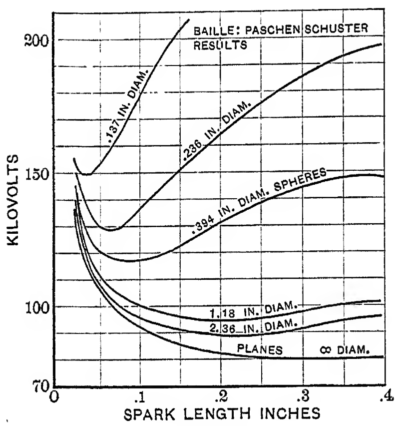


FIG. 6

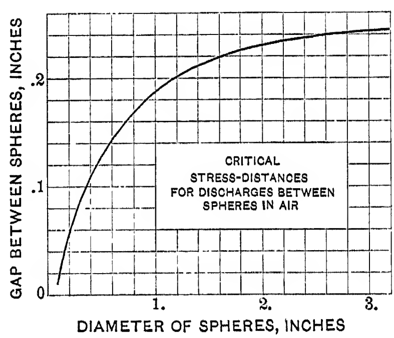


FIG. 7

the modern results by concentric cylinders in producing coronas and related spark-discharges with the old Baille-Paschen-Schuster results obtained by sparking between pairs of spheres and parallel plates. In doing this we find a practical agreement throughout. Between concentric cylinders the electric field spreads uniformly; between spheres it spreads more rapidly to the mid-point and then contracts in the same fashion to the near surface of the opposite sphere. The differences between these two classes of fields are largely of a compensating character,

*Baille, Annales de Chemie et de Physique XXV p. 486, 1882; Paschen, Wied. Ann. XXXVII p. 79, 1889; Schuster, Phil. Mag. V. 29, p. 182, 1890; and quoted by J. J. Thomson, Conduction of Electricity through Gases, first edition p. 287–9.

so that in *voltage—distance* effects they are not widely different after all. The fields between parallel planes are simply special cases of either the concentric cylinders or opposing spheres wherein the diameters are infinite. It must follow, therefore, that a curve located by the Baille-Paschen-Schuster values of diameters and the corresponding striking distances at minimum surface stress should be reasonably in accord with the curve of conductor diameters and corona striking distances, *i.e.*, distances from the surface of the conductor to the critical stress, 76 kilo-volts per in. zone. Such a curve is located in Fig. 7. It is of value and interest to note the almost exact agreement of these curves for diameters under *one quarter inch* (6.35 mm.). For example by the Fig. 7 curve, the spark discharge distance at minimum stress between spheres, 0.25 in. (6.35 mm.) diameter, is 0.063 in. (1.6 mm.), while the corresponding corona striking distance for a conductor, 0.25 in. (6.35 mm.) diameter, as given by the curve in Fig. 2, is 0.066 in. (1.67 mm.). Though alike in general character throughout, these curves differ totally in regard to the diameter at which the effect corresponding to part-corona makes its appearance. In corona formation about a round conductor the part-corona effect appears when the diameter has increased to about *one quarter inch* (6.35 mm.) while in spark discharges between spheres of all sizes the corresponding effect does not fully develop under a spherical diameter of *two and three-quarter inches* (7 cm.). The difference is due to the configuration of the two classes of electric fields. This is an important matter that will be taken up again in accounting for the descrepancies between corona formation results obtained by concentric cylinders in the laboratory, and by tests on the actual transmission lines.

These results no longer permit doubt to remain in regard to the fact that the electric stress required to rupture thin films is greater than the critical stress of 76 kilovolts per in., which, when uniformly distributed, is the stress required to rupture air in bulk. These results, however, do not indicate that this is due to an inherent difference in dielectric properties of air in a film and air in a bulk. They point strongly toward some dynamic action that requires a critical *minimum combination of stress and distance* through which to bring about rupture wherein any foreshortening of distance must be compensated for by an increase in stress.

At this stage of the study it became increasingly evident that

the *initial corona striking* distance is a factor of real importance in the control of corona formation. It must be understood as fully as the effects of stress are now understood in order to make progress in the subject.

II. Evidence that Electric Stress is but One of Several Factors of Importance in the Production of Corona and Spark-discharge in Air or in Gases Generally

a. Recent Results and Views of Nipher. At this point a copy of the second part of Professor Francis E. Nipher's classical paper "On the Nature of the Electric Discharge".* was received. For years, by methods that have been unique for their directness and simplicity this eminent physicist has studied the nature of the electric discharge. Most physicists who have studied these phenomena employed air or other gases in a highly attenuated state. The consequence is that great difficulties

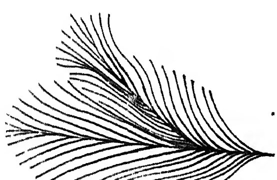


Fig. 8

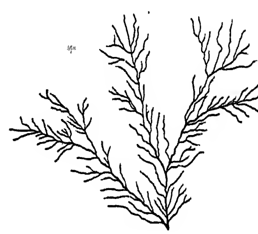


Fig. 9

are encountered when the attempt is made to apply their results to air under normal conditions.

Nipher's work has been done in air under ordinary normal indoor conditions. His results in the above paper show clearly the several dynamic features of the electric discharge in air. Among other important things he clearly establishes a direct relation between the electric discharge phenomena observed by him in normal air at a pressure of 29.5 in., (750 mm.) of mercury and those obtained by others at 0.04 in. (1 mm.). This paper made it possible to look to the authorities on the conduction through gases in attenuated states for knowledge in regard to corona striking distances, part-corona, discrepancies between results by concentric cylinders and parallel cylinders, meteorological factors, *et cetera.*

Nipher says that "the dissymmetry in discharge effects at

*Nipher, Trans. Acad. Sci. St. Louis, Vol. XIX, p. 57, June, 1910.

the *positive* and *negative* terminals of an electric machine is now ascribed to the difference in the size of the carriers of the electric discharge," and that the evidence presented in his papers "shows that the dissymmetry is due to the fact that the negative electrons are being forced out under '*pressure*' at the negative terminal and that they are being *drawn in* at the positive terminal under conditions which may be likened to those on the exhaust side of a pump." Figs. 8 and 9 were traced from sections of Nipher's photographs of negative and positive discharges splashed from electrodes over the sensitive films of ordinary photographic plates. One sees at once in these records some cause for the above conclusion. In the *negative* splash, Fig. 8, the discharge lines are characteristic of an outward fluid flow in a vigorous dynamic state or stiff, almost unbending forms. In the corresponding *positive* splash the reverse dynamic condition holds—that of an inward gravity fluid flow in a weak state, dynamically, and easily deflected.

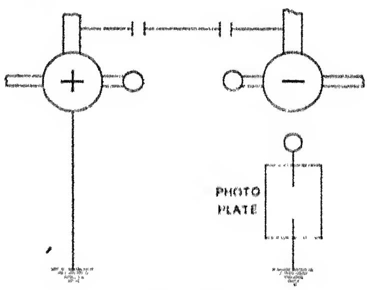


FIG. 10

The results recorded by Nipher in the photographs reproduced in Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b*, and 14*c*, are of especial interest in connection with the corona problem of the high-tension engineer. These photographs were produced in the following manner: In each case a common photographic plate was supported, film side up, on proper insulators a few inches above the surface of a laboratory table. At the center of the plate about 4 in. (10 cm.) apart, two common pins "dry-goods" type, were mounted vertically. The pin heads were in contact with the film of the plate and the points were soldered to wires, one leading through a short air gap between metal balls to the negative terminal of the electrostatic machine, and the other to the ground; the positive terminal of the machine was also grounded. This general arrangement is shown diagramatically in Fig. 10. By trial and experience in driving the machine a great variety of discharges could be made to pass between the pin-heads through the air over the surface of the photographic plates. The discharges could be made by rushing one or two sparks across the air gap in the negative circuit and the photographic plates

would record all the more important effects, since such effects are fortunately photo-active. The spark-gap length between the balls was adjustable and by turning the machine at various speeds every desired strength of discharge could be splashed through the air over the surface of the photographic plate. In this manner, then, the discharges were made that are photographically reproduced in Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b*, and 14*c*.

This short series illustrates beautifully, practically every essential form of electric discharge that can occur through air except the ordinary *arc*, a near approach to which has occurred in Fig. 14*c*. One sees at once in these records cause for the above conclusion quoted from Nipher. The details of what happened in the discharge records of Figs. 11, 12*a*, 12*b*, and 13, as they are understood by the author, after a study of Nipher's and of other physicists work in air highly attenuated for experimental convenience, and the recent corona results of Mershon, Watson, Whitehead and others under an approach to engineering conditions, are as follows:

Figs. 11, 12*a*, 12*b*, and 13 are records of the same discharge phenomenon, each differing from the other merely in magnitude. They can properly be discussed together. The application of an e.m.f. between the pin-head electrodes results initially in the formation through the surrounding air of a field of electric stress. The glass photographic plate intensifies the field in the air next to it because of its high inductive capacity. The form of this field under the circumstances is fairly familiar to us all. In the air next to the photographic plate the initial electric field set up is very much the same as that produced in the open air between two identical parallel round conductors and mapped by the familiar Faraday tubes of force in Fig. 27. Irregular throughout as this field is, it is nevertheless practically uniform in any concentric zone near each electrode. When an e.m.f. is applied between the pin-head electrodes high enough to produce one of these splashing discharges the electric field formed through the air film under and over the edge of the pin-head, between it and the glass photographic plate is strong enough to detach some electrons from the negatively charged pin-head and eject them outward through the near-by radially uniform electric field. These initially ejected electrons strike everywhere within ultramicroscopic distances atoms or molecules of air which they "*ionize by collision*," *i.e.*, each electron that strikes an atom of air in a stress above 76 kilovolts per in. does so at sufficient

FIG. 11

FIG. 12a

FIG. 12b

[Ryan]

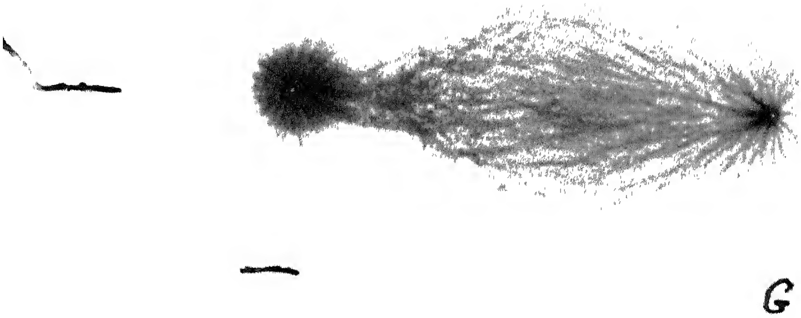


FIG. 13

FIG. 14*a*

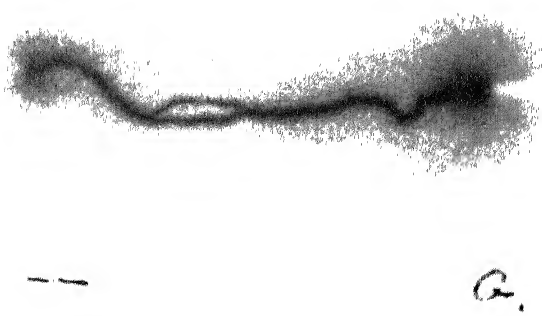


FIG. 14*b*

FIG. 14c

FIG. 29

[Ryan]

velocity to detach from such atom an electron. Two new ions are thus formed; the negative electron, and the neutral atom that lost it and which was thereby given a corresponding positive charge and became a positive ion. This new positive ion, being large, winds its way inward rather slowly to the negative electrode taking little part in the process of ionization by collision as will be seen later; the electron or negative ion, being small and in a field of ionizing stress is accelerated radially outward to collide with the next atom thus taking up its part in the spread of the ionizing process which in this fashion builds up rapidly by geometric progression. Ionization by collision is always accompanied by luminosity and is the cause of visible corona, part-corona, brush discharge, sparks and ultimately arcs.

Beyond the zone of luminous discharge at the negative pin-head the electric stress has fallen below 76 kilovolts per in. and new ions are no longer formed. By migration in the dark or "diffusion" as the physicists call it, in weaker portions of the electric field, this crop of electrons just formed continues to move toward the positively charged pin-head. Such migration is inherently an erratic process, setting up unstable forms of progress through the air, always following, turbulent fashion, the line of least resistance just as a batch of water does when splashed over an incline. The electrons in advance push aside the atoms of air and thus core out routes by which it is easier for those behind to pass. When it is remembered that these streams of electrons are the equivalent of conductors carrying currents it is easy to comprehend the manner in which they enormously alter and concentrate the normal stress of the electric field along their routes leading in erratic fashion toward the positive electrode. Such inward flow electron streams form about themselves magnetic fields that take up the role of closed elastic contractile envelopes that contract them into thin streams. The dark passage of electrons through the air is thus seen to be an erratic, turbulent process that in advanced stages cores out certain narrow channels of flow which simultaneously and completely modify the distribution of the electric field.

The electrons migrating in diffusion toward the positive electrode, are impelled everywhere by the stress of the electric field as modified by their presence; they strike everywhere atoms of air; everywhere they repel one another because they are each a negative charge of electricity. A turbulent process of this sort has its mechanical tendency to core out certain routes. Such

tendency is augmented by the magnetism that must, from the start, accompany the formation of each electron-stream. Everywhere, when the *stream-forming role of the magnetic-mechanic action* is stronger than the diffusion role played by the electrostatic attraction of neutral atoms and of mutual repulsion, the electron streams will form. The magnetic-mechanic actions tend to unite the little streams into larger ones while the electrostatic forces will tend to keep them apart. In air, at a density of *one atmosphere* and with a *sufficient crop of electrons*, the magnetic-mechanic contractile role exceeds the electrostatic diffusion role, streamers form, unite and produce a solid spark. In air at 1/760 *of an atmosphere*, even with the largest crops of electrons, the magnetic-mechanic contraction forces fall below the electrostatic repulsion forces and glow discharge, only, results.

When electrons conducted by diffusion unite to form streams, the stresses of the field are enormously localized through such streams which act as conductors, with a corresponding increase in the driving force applied to the electrons in the streams. When these velocities thereby produced exceed the velocity required to ionize by collision, the banks of the streams become luminous through such process. On the banks new electrons are liberated to join the stream and a corresponding lot of positive ions of atomic size are created and migrate counter current fashion. When conduction by diffusion remains as such and fails to form streams, as it will fail to do in a sufficiently attenuated atmosphere, ionization by collision will also form when the field is strong enough to produce the ionizing velocity of the electron in its run between collisions, *i.e.*, in its free path. Glow discharge is then witnessed and there are formed diffused, opposing "*electrical winds*" of the positive and negative carriers. In beautiful experiments Nipher has demonstrated the presence of these winds.

The behaviors in the normal atmosphere above referred to are photographically recorded by Nipher as shown in Figs. 11, 12*a*, 12*b* and 13, each being a different degree of the same splashing discharge phenomenon. As stated before, one can best see all the features noted above for himself by studying these records carefully. The formation of small non-uniting streams occurs at the in-flow of the positive electrode in Fig. 11. In the slightly larger corresponding discharges of Fig. 12*a* these streams have united to some extent just before reaching their goal; their numerous sources are in the general outer region of non-luminous

diffuse electron migration. Fig. 12*b* is a record made by a slightly larger discharge. In the discharge recorded in Fig. 13 the magnetic-mechanic forces exceed the electrostatic forces among the outward streams *at the negative* electrode on the side facing the positive electrode. Diffusion in that region was thereby not permitted. A group of electron streams is held together at first somewhat compactly, later more loosely as they extend to the positive goal. This is the approach to the formation of a spark.

The discharge that is recorded in Fig. 14*a* is most interesting because it shows up so clearly the mechanism of a spark in the normal air. The magnetic-mechanic forces closely confined a part of the electron crop on the side of the negative electrode immediately opposite the positive electrode, and caused such electrons to core an irregular route through the air extending somewhat over half the distance between the electrodes to a point where the forces of repulsion gained the ascendency and the spark broke, discharging its ions in diffusion toward the positive goal. The velocities remained great enough to produce luminosity. It is of great interest to note the shadow in this luminous electric wind that was cast by the positive pin and pin head in line with the discharge from the muzzle of the spark. Nipher recorded hundreds of these discharges that included sparks in all stages. He says that in every case the spark never completely extended to the positive electrode. Upon occasion sparks were recorded that extended but a fraction of an inch, *i.e.*. $\frac{1}{4}$ in. (6.35 mm.) more or less, from the negative electrode then broke into diffusion to complete the discharge over the rest of the distance to the positive electrode.*

A rational relation has now been established between electric discharge phenomena in the normal atmosphere that concern the electrical engineer and the corresponding phenomena that occur in highly attenuated atmospheres that have been studied with great care by many able physicists. The engineer can, therefore, confidently look to the results obtained by these men for much assistance in the further solution of the corona problem.

b. Townsend's theory of ionization by collision and its experimental verification; accounting for the great dielectric strength of

*An appendix to this paper reprints Nipher's resume of his papers on "The Nature of the Electric Discharge" published in Science, N. S., Vol. XXXII, p. 608, Oct. 1910.

*thin envelopes of air covering conductors and the details of corona formation.**

Townsend, after a thorough study of the whole range of phenomena produced by the conductivity of gases formulated and successfully verified the following theory of *ionization by collision* to account for a large and important class of these phenomena. For the present purpose this theory will be best understood by the consideration of a particular example:

Two parallel plane-faced electrodes are mounted with an atmosphere between them sufficiently attenuated to permit a convenient experimental study of these matters. By any suitable means, *viz.*, ultra-violet light, condensed radium or thorium emanation *et cetera*, *electrons* are liberated from the inner surface of the negative electrode at a definite rate, *i.e.*, a definite number of electrons liberated per square centimeter per second. A uniform electric field can be established between the plate electrodes and varied from zero to any desired maximum by connecting to the electrodes a source of correspondingly variable e.m.f. The parallel plate electrodes are so arranged that their distances apart may be adjusted accurately through any desired range. A proper form of galvanometer is connected in series with the e.m.f. circuit leading to the electrodes so that the current carried by *ions* through the column of air between the plates may be correctly observed. The negative ions are the electrons, *i. e.*, definite negative charges of electricity attached or unattached to neutral atoms dependent upon circumstances of a turbulent character and the positive ions are neutral atoms having lost each one or more electrons—generally only one. The section of the air column between the plates is confined by suitable solid dielectric walls so that its section is equal to the face of either electrode.

With electrons being liberated at a certain rate from the face of the negative electrode, as the field between the plates is increased from zero, the electrons are made to migrate toward the positive electrode and a corresponding current is indicated by the galvanometer. For a certain extent the current increases with the increase in the electric field. A strength of field is soon attained, however, that is sufficient to permit no electrons to go astray and to make them all migrate to the positive electrode. Further increase in the electric field produces for a time no cor-

*The Theory of Ionization by Collision by J. S. Townsend. Trans. Int. Elec'l Congress. I. p. 106. St. Louis, 1904.

responding increase in the electric current passing between the plates; this relation continues until the electric field has been increased to the amount sufficient to accelerate the electrons to ionizing velocity while being driven through the intra-atomic distances in the attenuated atmosphere. After that, further increase in the electric field is accompanied by a rapid increase in the current indicated by the galvanometer as flowing between the plates and the discharge which, throughout has been continuous, is now accompanied by luminosity. The last is the corona stage. These relations of the current to the electric field are given by the curve drawn in Fig. 15*a*. This general statement of the facts has been necessary in order to appreciate Townsend's theory of ionization by collision and its verification.

At the beginning of the corona forming stage, the strength of the field has become sufficient to accelerate the electrons in their free paths among the atoms of the air or other gases to the velocity that produces new ions when they collide with atoms in their paths. At each collision, as stated above in discussing the Nipher records, two new ions are formed; one, *negative*, *i.e.*, the newly detached electron, and the other *positive*, *i.e.*, the neutral atom that lost such electron by the collision. Under the action of the electric field these new ions begin their migration toward their respective electrodes of opposite polarity; in so doing each will collide with other atoms and will produce correspondingly at every such collision a new pair of ions when the free path traversed has been sufficient to gain ionizing velocity. Often an electron and a positive ion meet at a relative velocity low enough to permit recombination when a pair of ions is lost in the formation of a neutral atom.

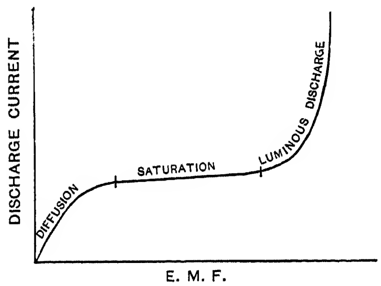


FIG. 15*a*

Since the mass of the positive ion is far greater than that of the negative ion, the electron, and since the driving forces applied by the field are alike in each case it follows that a positive ion will attain ionizing velocity only when accident gives it a free path between the atoms that is sufficient, and which in any event must be much above the free path required by the electron to produce new ions. The number of ionizing collisions

made by a positive ion in migrating a unit distance will, therefore, be far less than the number of such collisions formed by an electron migrating through the same gas, field and distance. In all other ways the positive ions take part in the phenomena of ionization by collision as do the electrons.

It follows that the increase of ions by collision must occur in geometrical proportion with the distance through which the action extends. In any given case, therefore, there must always be a limiting distance at which this increase approaches infinity, *i.e.*, a distance between the electrodes in which all of the atoms are ionized, resulting in the formation of a *spark or arc*. This is the *upper limit* at which the theory of Townsend ceases to apply; the *lower limit* began at departure from the saturation current caused by the production of additional ions by collision. See Fig. 15*a*. If the striking distance between the electrodes is shortened the same result, *i.e.*, a fully developed discharge, can only be produced by increasing the strength of the field by a compensating amount. The effect of so doing is to lessen the interatomic distance required to produce the ionizing velocity of the electrons: The number of collisions is thus increased to a degree sufficient to compensate for the loss in distance in which to bring about general ionization. To perceive this clearly one must remember that the paths between the atoms open to the free movement of the electrons or other ions are of all variable lengths, from zero to some *average maximum*. The lowest electric field or electric stress at which ionization is possible is that which accelerates the electron to the ionizing velocity when traversing these longest free paths; the great majority of other free paths are too short to effect sufficient acceleration. With increase of the electric field shorter paths become effective so that increase in field strength or electric stress makes available shorter free paths, increases intensity of ionization and lessens the minimum corona or spark-striking distance. The greatest limiting distance within which a spark can not form except with increased field occurs when the electric field or electric stress is at the critical value below which all ionization must cease because the velocities imparted to the electrons between collisions are not sufficient to detach electrons from neutral atoms.

This then is the underlying cause for the existence of *the limiting corona striking distances* charted in Fig. 2 or for those effects that lead one earlier to assume the existence at the surface of the conductor of a *thin zone of air having remarkably great dielectric strength.*

From such theoretical considerations Townsend derived the following expression for the relation between conductivity and distance through a gas wherein the electric stress and mechanical pressure of the gas, the initial ions and the rate of ionization by collision in excess of recombination are all known and fixed at possible values or values convenient for experimental purposes:

$$n = \frac{n_0 (\chi - \beta)\, \epsilon^{(\chi - \beta)d}}{\chi - \beta\, \epsilon^{(\chi - \beta)d}}$$

Wherein

n_0 = the number of negative ions starting from a small surface of the negative plate electrode.
n = the number of ions passing through the corresponding section of the gas between the parallel plain conducting electrodes; this number is proportional to the current set up.
β = the number of new ions produced per centimeter in passage of a positive ion through the gas to the negative electrode.
χ = the same corresponding value for electrons or negative ions.
d = the distance between the plates in centimeters.
ϵ = logarithmic base.

Townsend showed that sparking must ensue when the denominator of the fraction in this expression vanishes for then the number of ions migrating per second from conductor to conductor becomes infinite. As a matter of fact the value of n can not actually become infinite; it is limited to the number of actual migrating ions when most of the atoms or molecules of the gas have become ionized. However, since such number is nevertheless very great the distance d' for such very great number of n and d for an infinite number of the same is so slight due to the nature of this expression that it is not necessary to distinguish practically between the two.

Placing

$$\chi - \beta\, \epsilon^{(\chi - \beta)d} = 0$$

the value of d for which n becomes infinite is, therefore,

$$d = \frac{\log \chi - \log \beta}{\chi - \beta}$$

This distance d is therefore the minimum through which a spark or corona can be struck by the given electric stress. To strike a spark or corona through a shorter distance a higher electric stress must be applied that will increase the values of χ and β and, therefore, diminish d.

Townsend made careful experiments to test the integrity of this theory. In one experiment the values of n_0, β, χ, *pressure* and *stress* were as follows:

n_0 = 1 negative ion per definite small portion of negative electrode surface produced by impact of ultra-violet light.

β = 0.0141 new ions produced per centimeter travel of each positive ion.

χ = 5.25 new ions per centimeter correspondingly produced by each negative ion; the new ions thus produced being precisely similar to those produced by the positive ions, except as stated above.

Kind of gas, *air*; pressure, *one millimeter of mercury*; above-critical electric stress, 350 *volts per cm.* applied between parallel plate electrodes at various observed distances apart, resulting in the establishment of an observed conduction or n ions per given small cross section of gas column corresponding to the small surface of the negative plate electrode whence originated by impact of ultra violet light, *one* electron or negative ion per second. The currents corresponding to n, in arbitrary units of experimental convenience and to the distances that separated the plate electrodes as observed in experiments and correspondingly calculated from the above theory by Townsend are tabulated in the following table:

TOWNSEND'S EXPERIMENTS WITH AIR AT ONE MILLIMETER PRESSURE AND A CONTINUOUS ELECTRIC STRESS OF 350 VOLTS PER CENTIMETER.

d in centimeters	0	0.2	0.4	0.6	0.8	1.0	1.1
Current determined experimentally		2.86	8.27	24.2	81	273	2250
Current calculated by above formula for n	1	2.87	8.3	24.6	80	380	2150

The results by experiment have been charted in Fig. 15*b*. They speak for themselves and constitute a remarkable confirmation of the theory of ionization by collision.

c. (1) *Application of the theory of ionization by collision under normal atmospheric conditions.* (2) *Density of air and gas and*

form of electrodes as factors controlling and limiting ionization by collision. (Includes limits due to stresses sufficient to detach free electrons from the metal electrodes, critical sharpness of needle points and corona quantity in relation to rupturing gradients.)

Curve *I*, Fig. 6 of the Baille-Paschen-Schuster results obtained long ago with no knowledge of electrons and gas ions locates the corona striking distances at critical electric stress in the normal atmosphere at about 0.76 cm. or 0.3 in., as against the above value of 1.1 cm. in air at a pressure of one millimeter of mercury. The corresponding critical stress was found to be 31.5 kilovolts per cm. or 80 kilovolts per in., a little higher than the value generally accepted by physicists, *viz.*, 30 kilovolts per cm., or 76 kilovolts per in. From this it follows that the minimum striking distance at critical stress changes but little for wide changes in pressure. Townsend's experiments make it 1.1 cm. at 1 mm., (0.434 in. at 0.0394 in.) and the Baille-Paschen-Schuster results make it 0.76 cm. at 750 mm. (0.3 in. at 29.5 in.). These results were obtained by the use of uniform fields to produce discharges between parallel plane plate electrodes.

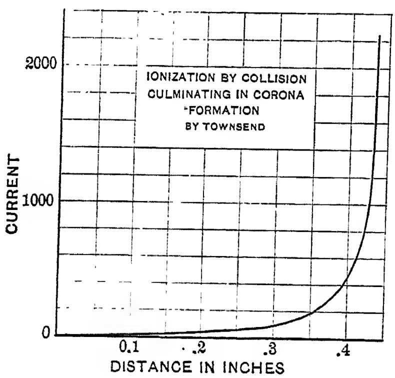


Fig. 15*b*

The same slow variation of critical striking distances between concentric cylinders at a given air pressure and critical stress made a great change in pressure at which the striking distance again became critical at critical stress.

Before going further in this use of the Baille-Paschen-Schuster results it may be well to note that at the time these observations were made as nothing was known of electrons, no radioactivity of the surface of the negative electrode was produced by ultra-violet light or other agency that would cause an initial source of electrons as was done by Townsend in his theory verification experiments. These results are on a parity with those of Townsend nevertheless, because they were obtained in the normal air, which under all ordinary circumstances contains radio-active material sufficient to ionize it somewhat. The necessary initial crop of electrons to be liberated at the cathode, is provided

by the impact of the incoming positive ions. Ionization by impact will be taken up later. Electrons thus liberated at the cathode are expelled from its surface and thereby made to begin the process of ionization by collision that culminates, when the field is sufficient, in the production of corona or spark discharge. The origin and importance in the corona problem of this universal radioactivity in the atmosphere will also be considered later.

From Townsend's theory as verified, it follows that in uniform electric fields between plane-faced parallel electrodes the minimum stress required to produce an electric discharge, *i.e.*, the critical stress, must vary directly as the pressure of the air or other gas. The critical stress is the one that can accelerate the electron in the average maximum free path to ionizing velocity. Such free path must vary inversely as the density of the gas, requiring in consequence that the accelerating force, *i.e.*, the electric field must vary inversely as the free path and directly as the gas pressure at a given temperature or inversely as the absolute temperature at a given pressure. *This relation holds between the following limits*:

For uniform electric field-stresses between parallel plane-faced electrodes.

The law holds for pressure down to somewhat less than 1 mm. (0.0394 in.) of mercury whereat the gas is too attenuated to maintain a definite average maximum distance between the atoms or molecules; the long free paths become indefinitely long and luminous discharge or corona ceases. The pressure limit upwards extends indefinitely. The relation holds correspondingly for electric stress downward—and upward likewise, until, because of the great density of the gas, the stress is great enough to produce a crop of electrons at the electrodes without being sufficient to increase their number by collision-ionization. This is in one of the wholly unexplored divisions of electrical knowledge. However, many things point to about 2300 kilovolts per in. (900 kilovolts per cm.) as the stress at which the electric discharge will be produced by ions torn from the metal electrodes largely regardless of the density of the air or other gas. This behavior will be considered further on.

For divergent electric field and stress between non-planar electrodes:

Between equal parallel cylinders and between spheres the critical striking distances are dependent upon certain factors that are controlled ultimately by the curvature of these elec-

trodes. This class of critical striking distances have been referred to earlier and are charted in Figs. 2 and 7. Critical striking distances for points, *i.e.*, electrodes having very small faces but of definite radii of curvature, have not been determined. The determinations are difficult and in the corona problem not of much importance. With pointed electrodes, however, two items of especial collateral importance in the corona problem have been brought out experimentally; and they are related to these critical distance-stress limits:

1. Fisher found that there exists a critical degree of sharpness for needle electrodes whereat the sparking voltage *for a given gap is minimum* being increased when this sharpness of the needle is either increased or decreased.* He found, for example, that with the voltage fixed at 6.2 kilovolts, (effective sine-wave) the 0.0015-in. (0.038 mm.) diameter fine needle point gave the longest sparking distance amounting to 0.422 in. (10.67 mm.) and with the voltage at 10 kilovolts (effective sine-wave), the 0.0017-in. (0.043 mm.) fine needle point gave the longest sparking distance amounting to 0.646 in. (16.4 mm.). The cause of this critical sharpness of needles used for sparking with a given voltage through a certain distance was found recently by the following method *to be due to the amount of the corona formed at the electrodes in relation to the sparking distance and voltage:*

The classical series of observations of Steinmetz was studied to secure data relating to electric discharge through the normal air using alternating high voltages and electrodes of opposing pairs of brass spheres of various diameters.†

It was noted that as long as the spheres of whatever size were so near together that the electric field between them was fairly uniform, the discharges were set up at about the normal critical stress of 76 kilovolts per in., produced of course by the maximum of the voltage waves. As the gaps were lengthened and the electric stress between the spheres became divergent the rupturing gradient, *i.e.*, kilovolts per inch between the spheres would drop rapidly to some low value, 10 to 4 kilovolts per in., (3.9 to 1.6 kilovolts per cm.), dependent upon the diameter of the spheres, being lowest for the largest spheres, and that it stayed

*H. W. Fisher, Spark Distances Corresponding to Different Voltages, Trans. Int. Elec'l Congress, Vol. II, p. 294, St. Louis, 1904.

†Steinmetz, Dielectric Strength of Air, TRANSACTIONS A. I. E. E., Vol. XV, p. 281, 1898.

at that value as the distance between the spheres was further increased as long as the balls were evidently not entirely enveloped in corona. Related phenomena of this character were then studied widely through the literature, including Fisher's careful observations on the electric discharge between needle points above referred to, the recent observations of Moody and Faccioli* on the voltage required to rupture the air between a round conductor mounted parallel to and at a distance from a metal plate as electrodes; including also unpublished commercial tests of high-tension suspension type, six to eight unit insulators, and accidents that produce discharges of great magnitude in the power houses and substations connected to high-tension networks.

This study in the light of our present day knowledge of such matters developed the following understanding as to the causes that effect the breaking down of the normal air in bulk by electric stresses that are so much below the critical stress. These bulk stresses range from 10 kilovolts per in. (3.9 kilovolts per cm.) for long gaps between needles, to 4 kilovolts per in. (1.6 kilovolts per cm.) or less between large spherical electrodes. The understanding of the matter is perhaps best presented by considering first the particular case of sparking between large spherical electrodes: As the gap between the spheres is lengthened, sooner or later, dependent upon the diameter of the spheres, the field becomes divergent. When the electric field has become decidedly divergent and the voltage required to discharge between the spheres exceeds that which is required to establish a critical stress in the envelopes of air covering the spheres to a critical depth, corona will be formed. It will appear first over limited portions of the opposing surfaces of the spheres. In this state at the negative sphere electrons are liberated by impact at its surface of incoming positive ions,—the first of these positive ions were of natural or "antecedent" origin. Ionization by collision follows and a crop of electrons results that is great enough to cause the magnetic-mechanic contractile forces to form an *electron core* against the diffusion forces of mutual repulsion, the attraction of neutral atoms and the counter electric winds of incoming positive ions. Such a core is the equivalent of a current in a conductor. The size of this core and its density of driven electrons are measures of the

*Moody and Faccioli, Corona Phenomena in Air and Oil. TRANSACTIONS A. I. E. E., Vol. XXVIII, II, p. 769, 1909.

equivalent current and the conductivity of the equivalent conductor. If the corona formation at the negative electrodes is sufficiently great, the core will have so high a conductivity that there will be voltage enough between the spheres to drive it clear across the air gap thus producing a discharge or arc. Now the greater the diameter of the spheres, the greater will be the area over which the corona will be formed and the greater the supply of electrons in stock, therefore, with which to drive the electron core or spark from the negative to positive sphere, the higher, then, will be the conductivity of the core and the lower the corresponding voltage gradient. It is a quantitative result that is quite independent of the figure and strength of the intervening field-stress which in many portions is less than one per cent of the critical stress. No evidence could be found that the intervening strength and figure of the electric field is more than a small factor among those that determine the voltage gradient required to rupture the normal atmosphere in bulk.

To assist the judgment which is ones chief resource in a study of this sort, the available data were charted in the order determined by rupturing gradients. This chart is reproduced in Fig. 16.

Returning now to Fisher's critical sharpness of needles: From a very finely tapered and pointed needle, corona is produced more easily but in smaller amounts at given voltages and spark gaps, than from the points of needles that are not so finely tapered and pointed. Thus it is seen that changing the sharpness of the needles affects oppositely the two most important factors that bring about the electric discharge through air or any gas, *viz.*:

(1) *Corona starting facility, dependent directly upon voltage* and (2) *rupturing facility, dependent directly upon corona quantity.*

An increase in the sharpness of the needle electrodes raises the former facility and lowers the latter, and *vice versa*. Thus at a given voltage there must always be some compromise degree of needle sharpness that will cause the discharge at such voltage to cross the longest gap—a discovery made experimentally by Fisher nearly ten years ago. With this understanding of the factors that control the (needle point gap) to (sparking voltage) relation the peculiarities of our standard A.I.E.E. spark gap voltage curve are easily comprehended as inherent and therefore necessary. The more or less definite degree of " sharps No.

6 " bluntness of point, end taper, main taper, straight shank and mounting all take their part in changing the supply corona and therefore of electrons as the gap lengthens and the discharge voltage increases.

The other item referred to above related to the critical distance-stress limits that is of interest in the corona problem may now be considered.

2. Some years ago experimental studies were made of the dielectric strengths of compressed air and carbon dioxide by

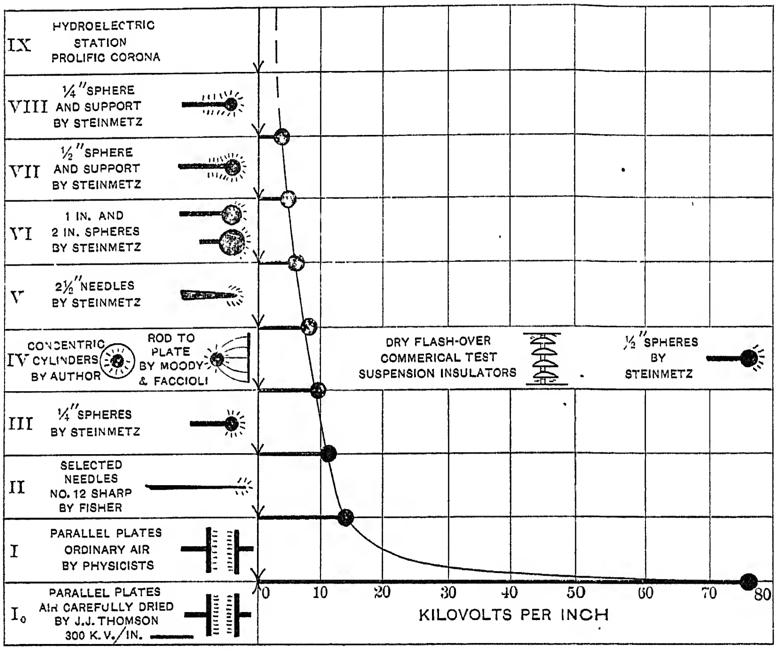


FIG. 16

the needle point spark-gap method.* A little later Mr. E. A. Ekern as a graduate student continued the experimental study along the same lines, with greatly improved facilities.†

In advance of these experiments it was expected that the dielectric strength of air and other gases increased directly

*Conductivity of the Atmosphere by H. J. Ryan. *Sibley Journal of Engineering*, Vol. 18, p. 267, 1904; amplified in lecture reported in *The Electric Journal*, Vol. II, p. 429, 1905.

†" Conditions which Influence Spark-potential Values," by E. A. Ekern. *Sibley Journal of Eng.*, Vol. 18, p. 391, 1904.

as the density without limit under the approach to liquefaction. The experiments determined, however, that quite independently of the actual density of the gas the discharges would always pass between the needle points at a voltage that would be approximately *ten times* the voltage required correspondingly to produce the discharge through the gas at normal atmospheric pressure. For the most part needle points were used as electrodes. The sharpness of the needle points was varied; the electrodes were changed altogether from needles to thin rods with round or conical ends and to small spheres; in each instance the discharge distances were varied. In all cases fundamentally the results were always much the same. As the density of the gas was increased at ordinary temperatures by increasing the pressure and with the conditions fixed as to length of gap,

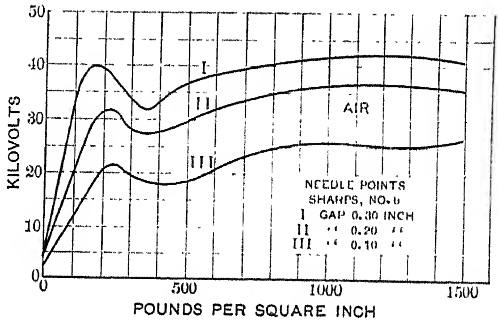


FIG. 17*a*

kind and condition of electrodes, the sparking voltage would increase uniformly until it became about 10 times the voltage required to produce a spark discharge at a pressure of one atmosphere. At this stage a great change in these relations would always occur. A set of results obtained by observations made with *air* at pressures varying from 1 to 100 atmospheres or 15 to 1500 lb. per sq. in. (1.05 to 105 kg. per sq. cm.) using needle points, sharps No. 6, at three different gaps are reproduced in Fig. 17*a* from the little paper by Ekern referred to above. The results of another set of observations in this class are charted in Fig. 18 reproduced from the lecture just referred to. The electrodes used in making this set were of aluminum wire, diam., 0.09375 in. (2.38 mm.), "points" spherical; gap 0.096 in. (2.43 mm.). The gas was *carbon dioxide* and the pressure was carried through from one atmosphere to 700 lb. per sq. in.

(49.2 kg. per sq. cm.). It was the last and best set of observations made in this class. Care was taken to eliminate disturbances introduced by the insulating supports of the electrodes, the walls of the container, *et cetera.* These results are fundamentally typical of all others obtained throughout the entire investigation.

At the time, no satisfactory explanation of the matter could be found. Now, however, the cause for the electrical failure of the gas at any density that requires for rupture about ten times the voltage that must correspondingly be applied to rupture at one atmosphere is understood to be as follows:

The conductivity of metals is due to the presence among their atoms of a certain stock of free electrons. In the metals the atoms and free electrons are very close to one another. The

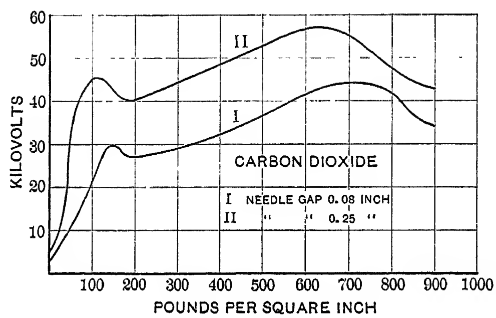


FIG. 17*b*

electrostatic attractions between the atoms and the free electrons are very great and do not allow the latter to leave the surface of the metal.* When the stress delivered from the metal electrode surface to the adjacent zone of gas is great enough some of the free electrons in the metal will be detached from the electrode and will migrate through the gas to the anode. From principles of action brought out above when this source of electrons becomes sufficient the magnetic-mechanic forces will retain them in a core that will develop a spark-discharge regardless of the stress required to ionize by collision at any particular density of the gas that may happen to be employed for the experiment. Doubtless the actual density of the gas is on some accounts, a factor

*The behavior of the discharge when the plate electrodes are very close together observed by Erhart and discussed by J. J. Thomson in "Conductivity of Electricity Through Gases." First edition, p. 386.

assisting, and on other accounts opposing this process and would, if thoroughly studied, completely account for the particular form of sparking voltage-pressure characteristic obtained for a particular form of electrodes. Such study should account for the drop in gradient that follows the first stop of its increase and of its subsequent recovery. These forms in the upper ranges vary widely as the shapes of the electrodes and the gases are changed. Throughout, for the most part, at *approximately ten times the normal sparking voltage*, the density of the gas ceases to be a factor, *i.e.*, ionization by collision or corona controlled by the gas density ceases to be a factor because a new source of electrons has developed, *viz.*, the liberation of those within the metal electrode. Once formed, electrons and positive ions migrate with great facility through gases at high densities under all values of electric stress.

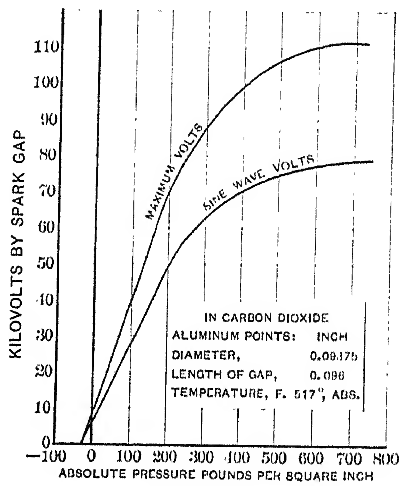


FIG. 18

The factors that bring about the detachment of the free electrons that exist in the metal of the electrodes are of great importance in some aspects of the corona problem. An understanding of the matter from a single view is not likely to be reliable unless it can be checked in various other and as far as possible independent situations. The conductors themselves as a source of ionization have been given almost no direct attention. The only data available in relation hereto have been obtained incidentally without conscious motive through efforts directed for other purposes. Erhart in the work just referred to mounted polished steel spheres at minute adjustable distances in air at various pressures from 0.02 to 3 atmospheres and observed the continuous e.m.f. required to spark between them. After the distances were so small that ionization by collision was no longer possible a discharge could always be produced when the air pressure was one atmosphere and when the stress was about

2,500 kilovolts per in. (1000 kilovolts per cm.)

The shortest distance and the lowest e.m.f. used were 0.000011 in. (0.00027 mm.) and 28 volts. In the one preceding this case there is no way of knowing with any reasonable degree of exactness the value of the stress at which the free electrons in the needle points were detached principally on account of the great disturbance of the field by the presence of a few native ions. An approximation may be made as follows: The discharge or corona striking distances for small spheres were determined from the Baille-Paschen-Schuster results, Figs. 6 and 7, to be about the same as those found for small round conductors given in Fig. 2.

From Fisher's results it was evident that the diameter of the sharps No. 6 needles used to obtain the Fig. 17*a* results had a diameter of about 0.002 in. (0.05 mm.), requiring as seen in Fig. 2 a striking distance of 0.02 in. (0.5 mm.) which is well within the shortest gap used in that set and requiring a *surface gradient* as seen in Fig. 1, of

2300 kilovolts per in. (90 kilovolts per cm.)

to rupture at one atmosphere. This makes the stress at which free electrons left the steel *needle* points in *air* 2300 kilovolts per in., (900 kilovolts per cm.). Using the later results obtained with one-tenth inch (2.54 mm.) aluminum wire, spherical points, one-tenth-inch gap in carbon dioxide, the pressure-sparking voltage relation started at 8 kilovolts at one atmosphere and went flat at 110 kilovolts, and 700 lb. per sq. in (42.2 kg. per sq. cm.). The striking distance is 0.06 in. (1.5 mm.), again well inside the length of the gap, the initial rupturing surface stress at one atmosphere is 160 kilovolts per in. (63 kilovolts per cm.) and the ratio of initial and final voltages is 13.7, making the surface stress at which the free electrons left the *aluminum wire hemispherical electrodes in carbon dioxide* 160 x 13.7 =

2200 kilovolts per in. (862 kilovolts per cm.)

These three cases occupy widely different situations and the results are in close agreement considering the circumstances. It appears a reasonable conclusion therefore that when the electric stress about a metal conductor in a gas exceeds 2000 kilovolts per in. (800 kilovolts per cm.) or therabouts, that the free electrons of the metal cathode will escape profusely into the gas and form a heavy discharge between the electrodes.

d. Stress from metallic electrode surfaces to dry high-tension insulating oil required to ionize and, therefore, to approach rupture by detaching free electrons from the metals of the electrodes.

It is of much collateral interest to know at what corresponding surface stress the electrons that are free within the metal electrodes will escape when such electrodes are immersed in a highly fluid dielectric such as high-tension insulating oil that has been carefully treated so as to remove all free ions as far as possible, *i.e.*, treated so as to raise its specific resistance under the stress of a continuous e.m.f. to the highest attainable limit. The intermolecular spaces of such oil are very much less than in gases except when the latter are near the point of liquefaction. The molecules of the oil would be in the aggregate much nearer the metallic atoms of the electrodes than in the case of a gas-immersed electrode. The free electrons in the metal would be attracted by the molecules of the oil as well as the atoms of the metal in greater degree than in the case of gas immersion. It seems reasonable to expect, therefore, that in oil at its very best the electrons should be drawn from the metal by the oil at a decidedly lower stress than the corresponding stress when gas is used. This view is supported by the fact that when gas is used the electron extracting stress drops considerably as the point of liquefaction is approached. Moody and Faccioli* experimentally studied the formation of corona about conductors immersed in high-tension insulating oil. The electrodes were wires, 15 in. (38 cm.) long and metal plates, mounted parallel, at a distance of 6.5 in. (16.5 cm.) from the center of the conductor to the face of the opposing plate. The diameters of the wires and the corresponding effective sine-wave corona producing voltages are given below:

Diameter		Kilovolts
Milimeter	Inch	
0.50	0.02	50
1.00	0.04	60
1.27	0.05	80
3.05	0.125	100

The corona formed about each of the first three small wires was maintained continuous, producing about them a highly

*Moody and Faccioli, " Corona Phenomena in Air and Oil." TRANSACTIONS A. I. E. E., XXVIII, p. 769, 1909.

ionized gaseous envelope. In regard to corona formation about the last wire, considerably larger than the others, it was said "the brush will appear at about 100,000 volts, and if we raise the potential the brush will appear and disappear again irregularly; that is we have an intermittent luminous phenomenon which represents more of an interrupted arc than the regular corona." * * * * "The large wires under oil, as we have said, give very unsteady and, therefore, unsatisfactory results."

Before giving the electrode surface stresses produced by the voltages at which these coronas under oil were produced it is necessary to understand the basis for comparing stresses that must be employed when changing dielectrics. All dielectric stress must be understood in terms of the strain it produces, *i.e.*, the displacement quantity or time-integral of charging current, *viz.*, the coulombs per unit-cube. In no other way can the terminal effects due to the substitution of dielectrics be properly compared. This system of designating strain as a result of stress is not as yet generally understood hence the necessity of stating resulting strain in terms of stress in air, the standard dielectric, that would produce the same strain in coulombs of charging current per unit air-cube. The specific inductive capacity of oil is about twice that of air. The strain in oil produced by a given electric stress is, therefore, about twice the corresponding strain produced by the same strain in air. To use the air as a standard for gauging electric strains it is necessary to multiply stress in other media expressed in voltage gradients, kilovolts per in., by their specific inductive capacities.

The following electrode surface stresses required to produce corona under oil were calculated from the above observations of Moody and Faccioli:

Diam.	Kilovolts	Stress in oil adjacent to electrode surface	Corresponding strain using air as standard
Inch		Kilovolts per in.	Kilovolts per in.
0.02	50	987	1974
0.04	60	1040	2080
0.05	80	830	1660
0.125	100	670	1340

The first three average a strain of 1900 kilovolts per in., (750 kilovolts per cm.) in the thin gas envelope surrounding the wires. The average of the above Erhart-Ryan-Ekern electron

extracting strains obtained in air was 2330 kilovolts per in. (917 kilovolts per cm.) These results are interesting though they are not those that are wanted. Ordinarily there must always be a few electrons escaping from metals immersed in oil to form ions that give rise to its so called insulation resistance because under thermal agitation some of the oil molecules must be driven close in among the metallic atoms so as to meet and capture some of the free electrons regardless of the amount of electric stress extending from the conductor into the oil. This escape of electrons into the oil is very small. When a sufficient electric stress is applied from the electrode to the oil the average maximum amplitude of the electrons swinging in an out of the surface of the conductor-cathode will be increased so as to bring them near enough to the oil molecules to be captured and prevented from returning to the conductor. This is the *critical liberating stress* that is wanted. Taking all the circumstances into account it seems reasonable to expect that such critical stress must be much below that which will be strong enough not only to liberate the electrons from the cathode but will also drive the ions thus formed in the oil away from the conductor with such violence as to resolve the oil into a luminous envelope covering the conductor with highly ionized and heated gas. With these considerations in mind the behavior of the 0.125-in. (3.05 mm.) conductor, the last in the above series, is not surprising. With this much larger diameter the stress is far less divergent, which facilitates the magnetic-mechanic electron core-forming process. Before general corona could be established one or more of these cores or brushes appeared at 100 kilovolts which the authors accepted as the corona starting voltage; it is, however, probably much less than that which would have enveloped the 0.125-in. (3.05 mm.) conductor with a covering of corona pervaded oil gas. The corresponding *strain* is much lower than the average of the three preceding cases, *viz.*, 1300, being but little more than *one-half* of the value found for the liberation of electrons from metal to air.

If oil-immersed electrodes of much larger diameter were used the electric fields would be much less divergent and the core forming would follow promptly upon the initial start of the electron liberation process as the stress is increased. It was found that Tobey had made dry oil rupturing tests using brass spheres as electrodes having two-inch (5-cm.) diameters set for

various gaps from 0.4 to 4 in. (one to 101 mm.).* The Baille-Paschen-Schuster results may be employed to obtain the constants that depend upon the figure of the electric field when spheres are used for electrodes. This saves a lot of mathematical work. In this way the stresses in the oil adjacent to the opposing faces of the spherical electrodes corresponding to the voltages that ruptured the oil were easily computed. In Fig. 19 Tobey's original voltage to distance curve has been re-drawn and the results obtained as above were used to locate in the same illustration the *surface stress* to *distance*, or *kilovolts per in.* to *inches* curve. It is natural that this relation should be totally

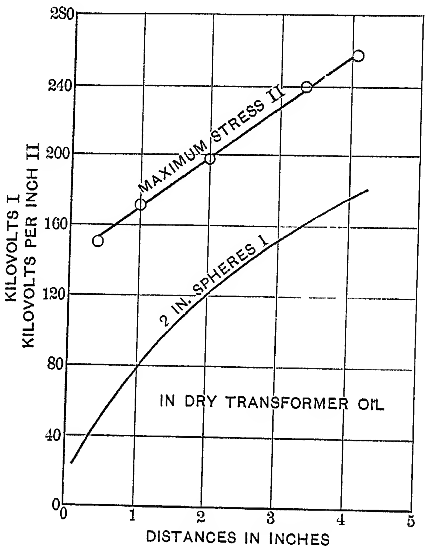


FIG. 19

rectilinear because the turbulent ionization by collision, the all important factor in electric discharge through air and gases generally, is absent or practically absent in oil. In air when electrons are liberated in corona formed only over the face of the electrodes the relation is rectilinear—a matter discussed earlier in this paper.

This right-line relation of surface stress and distance between the two-in. (5-cm.) brass spheres holds upwards from 0.4 to 4 in. (one to 101 mm.); if it also holds downwards indefinitely,

*W. H. Tobey. Dielectric Strength of Oil. PROCEEDINGS A. I. E. E., July 1910, p. 1171, Fig 6.

as it seems reasonable to expect that it should, then the stress at which electrons are liberated from metals into dry high-tension insulating oil is 140 kilovolts per in. (55 kilovolts per cm.).* This is a most surprisingly low value—and if fully verified will form a basis upon which to account for the behavior of the oil switch; it may also have an important bearing upon the design of oil-filled insulation spaces in high-tension transformers to prevent the slow disintegration of oil and solid insulation.

III. Electrons, Ions and Ionization

a. The fundamental purpose of this paper is to discuss the high-tension transmission corona problem in the light of the evidence available at the date of its preparation. The foregoing foundation was placed to support this discussion and is necessarily incomplete. In some respects it is incomplete for lack of further knowledge, while in other respects it is incomplete because it is not effective to treat too many related things at one time. For this reason certain things have heretofore been merely mentioned or consciously omitted and will now be considered more fully.

The important part that ionization plays in all phenomena that lead to the formation of corona is now clear. The corona phenomena that remain to be accounted for are of such a character as to require for their ultimate understanding a thorough knowledge of the origin, inherent qualities and characteristic behaviors of ions, *i.e.*, of the electricity carriers in gases.

Every material substance is made up of atoms or their elemental aggregations, molecules. Each kind of substance has certain distinctive characteristics because of some structural

*Attention was not directed to these phenomena in oil until well toward the close of the preparation of the present paper. Time did not then permit a careful laboratory study to determine whether the rupturing surface stress to distance curve, *II*, Fig. 19, does or does not remain a right line locating a limiting surface stress, in this particular case, of 140 kilovolts per in. (55 kilovolts per cm.) at zero distance between the spheres. Some experiments of this sort were hurriedly performed using dry transformer oil between two-in. (5-cm.) polished steel cylinders at distances varying from 5 to 20 mils. Difficulty was encountered in an effort to obtain consistent results, apparently because of the ease with which the metallic surfaces would capture films of ionized gas at the first application of the electron-detaching stress. The results indicated, however, that the right line, Fig. 19, curve *II*, descends to the vertical axis locating a critical stress of 140 kilovolts per in. (55 kilovolts per cm.) from brass surfaces to high-tension insulating oil as stress and strain required to detach free electrons from metals.

character of its atoms. All kinds of atoms have one feature in common. Each atom holds through electrostatic attraction a certain number of relatively minute particles. The number of these particles is different for different atoms. Each particle is the ultimate and non-detachable terminus of a certain definite tube of electric force or, as some would say, it is the seat of a certain definite electric charge. The amount of this charge is 4.65×10^{-10} electrostatic units—perhaps a little larger, not exceeding 5×10^{-10} electrostatic units. In the literature of the subject this ultimate particle of matter is burdened with two names *electron*, the one apparently in more general use, and *corpuscle*, the original term used consistently by some of the best known physicists. The frame of the atom is the whole of the atomic structure less the electrons and their non-detachable electrostatic fields. The atomic frame is the common anode terminus of the electric fields or tubes that constitute an essential part of the electrons. The anode terminus of the electron field is, if not altogether detachable, at least transferable from one atomic frame to another.

A positive ion is formed when any neutral atom, molecule or atomic aggregation has, through any cause lost one or more electrons—usually but one. It thus becomes a positively charged ion. If the gas in which it is located is pervaded by an electric field it will be subjected to a corresponding force that will cause it to migrate in the general direction of the cathode or negative terminus of the field. The smallest positive ion is, therefore, a single atom that has one less than its normal quota of electrons. The largest may be any aggregation of atoms or molecules held together by the electrostatic field due to the loss from the normal stock of the aggregation of one or at the most a very few electrons.

A negative ion is any free electron, or any atom or unit atomic aggregation that has captured electrodynamically one, or at the most, a very few electrons more than the supply that constitutes the neutral atomic state. The smallest negative ion is a single electron—vastly smaller, therefore, than the smallest positive ion. The smallest positive and negative ions are alike, therefore, in the charges they carry and forces with which they are drawn through a common electric field. In sizes and masses of the smallest ions, the positive is, therefore, far greater than the negative ion. It follows that the mechanical activity of the smallest negative ion is far greater than that of the smallest positive ion.

In the open air, the natural ions present are in a comparatively quiescent state. By their electrostatic forces they have captured various molecular aggregations, generally made up *mostly, though not necessarily, of water.* These captured aggregations are retained while the dynamic activity of the ions is low. When, however, this activity is increased, by the presence of a sufficient electric field, such as is comparable with the fields set up about high-tension circuits, the forces that have captured and retained the aggregations are no longer sufficient to hold them and they are lost. Thus it occurs that all ions that take direct part in the corona formation or in the essential phenomena that precede the corona state are only those of smallest size, *viz.*, the electron and the neutral atom less an electron. This is so because all such phenomena are brought about by ions in a high state of electrodynamic activity.

The ionization of the atmosphere in the open has been and is now being studied to an enormous extent by meteorologists and physicists. The former have direct need of the most complete knowledge of the ionization of the air while the latter are particularly interested in the radioactive character of the various emanations of radium, thorium, *et cetera*, that are constantly escaping into the atmosphere from the earth. The following nomenclature has been proposed for ions of the various sorts physically that are found native in the open air:

"Let the ion formed of atom and electron be called a *nucleolus*, such an ion surrounded by molecules forming a solid or liquid mass be called a *nucleus*, and let a collection of molecules in the form of a vapor round a nucleus or nucleolus be called an *envelope*; then the three types of gaseous ions are (1) *nucleolus alone*, (2) *nucleolus and envelope, and* (3) *nucleus and envelope.* The third type merges into the visible drop of fog and rain."*

b. Sources of Ionization about High Voltage Transmission Lines.

These sources are:

1. *Radioactivity* that is entirely natural in the open air.

2. *Impact* of ions at the surfaces of conductors caused by the electric field.

3. *Collision* of ions and atoms when the field exceeds the critical ionizing strength.

As already stated the radioactivity that is always producing

*W. Sutherland, "The Ions in Gases." Phil. Mag. 18. pp. 341–371, Sept. 1909. Quoted from Science Abstracts No. 1731 p. 584, Oct. 25, 1909.

ions in the open air is due to the presence of emanations that are constantly escaping from the earth and subject to rapid radioactive decay. Every conductor exposed in the open collects upon its surface some of these emanations—the real essence of the " dirt " that causes the cathode conductor to start *part-corona* at abnormally low voltages. The emanations carry positive charges and are captured in abundance and retained by negatively charged conductors mounted in the open.

On land the radioactive emanations escape everywhere directly into the air. All underground waters absorb these emanations. Under the sea, lakes and rivers the emanations that escape from the earth are absorbed by the water. In porous rock formations, particularly of recent volcanic origin these emanations escape more plentifully. During the rising barometer air is being forced into the porous earth's crust; at this time a noticeable falling off of the ions in the air occurs due to a partial suspension thus produced of the supply of radioactive emanations. When the barometer is falling air is withdrawn from the earth and with it the accumulated emanations. At such time the ions present in the atmosphere are always observed to increase.

The emanations absorbed by the sea, lakes, *et. cetera*, are liberated plentifully along the shores or elsewhere when agitated by breakers, white-caps and waterfalls.* Ions from these water sources are apt to be heavily laden with water and will behave more or less in a class by themselves.

The degree of ionization as affected by radiations arriving from cosmic space has been studied in some respects during recent total eclipses of the sun. There are effects of this character though they constitute a small factor in the corona problem.

The escaping emanations carry positive charges. The result is that the earth whence they escaped must carry a negative charge. The positive and negative ions that are formed in the air by the radioactive decay of the emanations are necessarily

*Wireless telegraphy is best conducted in an atmosphere free of ions. The ions present are driven back and forth by the electric oscillations thereby dissipating their energy. Wireless stations will not do so well by the sea, on porous volcanic earth nor at high elevations. The earth is negatively charged, which causes a concentration of the radioactive emanations and their ions over all elevations. These results in wireless telegraphy have been reported to the author by experienced men in the San Francisco Bay region.

about equal. In addition to these are the positive ions that constitute the ionizing emanations. Such a state gives rise necessarily to a positive charge of the atmosphere relative to the earth. Near the surface of the earth there is thus produced an electrostatic field that forms a potential gradient of about 20 volts to the foot or about 70 volts per meter. In the upper regions of the atmosphere the difference between the quantities of positive and negative ions present per unit volume is greatly diminished due probably to the fact that the emanations that reach the upper atmospheres are well on the road toward complete decay; probably, to some extent, also, because of the downward forces exerted on all positive charges by the field. The consequence is that the electric field in the upper regions is greatly diminished; it is estimated by specialists to be practically zero over land of usual topography at an elevation of about 50,000 feet, (15 kilometers). Fig. 26 is reproduced from a paper of Liebenow read before the Elektrotechnische Vereins.* The curve in this illustration gives the strength of the earth's electrostatic field in relation to altitude. The vertical values designate the fields in volts per meter and the horizontal values the elevations in kilometers. The original chart was expressed in different units. The slope of this curve at any altitude is proportional to the number of positive ions present per unit volume at such altitude in excess of the corresponding number of negative ions. The actual number per cubic inch even near the earth's surface required to account for the changing gradient, *i.e.*, for the existing electrostatic field as a whole, is quite small, *viz.*, about 30. In any event the number could not be larger because of the extraordinarily small quantities in which the emanations occur. Curve II in this illustration is the integral of curve I. It shows that the potential of the earth is 164,000 volts, negative. It is found quite generally that the ionization of the air is higher on mountains. This is manifestly due to the negative charge of the earth; the mountains act like sharp projections from the surface of "*the charged conductor*" in the familiar electrostatic experiments that delighted our forefathers; they concentrate the earth's electric field which in turn concentrates the radioactive emanations thereby frequently causing a very high degree of ionization. Among high mountains the ions in the air will, therefore, vary

*C. Liebenow, "Uber tellurische Elektricitat." Presented at a meeting of the Elektrotechnische Vereins Oct. 23, 1900. Reported in the *Elektrotechnische Zeitschrift*, Nov. 15, 1900, p. 962.

greatly. The electric field, and therefore, radioactive emanations in the canyons will be smallest and on the peaks highest.

Any considerable change in the altitude of a transmission line must also constitute a corona forming factor. An extreme case would be that of a hydroelectric plant located in the Sierras at an elevation of 8,000 ft. (2438 m.) delivering its power to the San Francisco Bay region high-tension network. From the potential curve in Fig. 26 it is seen that the atmospheres at opposite ends of this line are at a potential difference of 100,000 continuous volts. At the sea level end such a line would have the average zero potential of the high-tension network. The air about the Sierra power house terminal would be at a continuous potential of 100,000 volts above that of the line. A large supply of radioactive emanations would be drawn toward and deposited upon the surface of the conductors, or held in suspension in their neighborhood. About the high altitude portion of the transmission line there would be at all times an abundant crop of native ions. The effect of this would be to increase the in-phase sub-corona diffusion current, or *convection current*, and to lower correspondingly the critical voltage at which part-corona would begin, though it would alter but little the value at which complete corona would be started.

On the other hand a short high-tension line erected on a mountain side, having small change in altitude, such as Mershon used in his high-tension atmosphere line-loss experiments at Telluride, Colo., in 1896, may escape all effects of the above class due to altitude. In fact such a high-altitude line, when located so as to be sheltered from the radioactive emanations that collect around the neighboring peaks and ridges may have a relatively higher than normal critical voltage at which *part-corona* will be started. At low barometric pressure *full-corona* will start at a corresponding lower voltage. On approach to such corona voltage the in-phase diffusion current carried by natural ions will be less, being approximately proportional to the voltage. The ability to "core up" or "brush" and thus to start part-corona depends upon the magnitude of this diffusion current; such ability will, therefore, be less. This brush or part-corona starting voltage is the *critical voltage* as defined by Mershon.*

From many laboratory experiments it is known that the part-

*Mershon, "High-Voltage Measurements at Niagara." TRANSACTIONS A. I. E. E., Vol. XXVII, II, 1908, p. 886, Fig. 38.

corona voltage range, *i.e.*, the difference between the critical voltage (Mershon) and the initially complete corona voltage varies much with the density of the atmosphere. The difference is decidedly less at two-thirds of the density of the normal atmosphere such as obtains at Telluride. It follows that the topographically protected short, high-altitude, high-tension transmission line will have a Mershon critical voltage above the normal, allowance having been made for change in density of the atmosphere due to the altitude and temperature upon which full-corona voltage directly depends.

In clear weather under average conditions there are found in the air over land about 32,000 ions of either sign per cubic inch (2000 per cubic centimeter) and over the sea about one half this number. Cloudy, sultry weather diminishes their number the smaller ions probably being captured by slow moving water and dust aggregation amounting, if this is so, to no real diminution. The evidence in regard to the rate at which ions are created is not concordant, apparently because of experimental difficulties in the way of distinguishing single ions from their aggregations. Perhaps the most reliable determination is that of Wilson who found in air, over land, enclosed, and dust free, 500 of either sign per cubic inch per second (30 per cubic centimeter per second).* Correspondingly in the air over sea the number of ions of either sign has been found to be much smaller, *i.e.*, about one fifth of the number correspondingly found on land. A recent authoritative work states that about 100 ions of either sign are created per cubic inch per second in air over land and from 15 to 30 correspondingly over sea.† Beyond the fact already mentioned that ionization of the air is increased to *ten times*, more or less, dependent on altitude, topography, *et cetera*, on mountains due to the negative potential of the earth, little is definitely known quantitatively of these matters at high altitudes.

d. Ionization by impact; its place in corona formation, as affected by absolute voltage and frequency.

Without the prior existence of natural ions in the air corona would not be formed except at extraordinary stresses, as has already been shown. It has also been shown that ionization by collision will build up an unlimited degree of ionization from an extraordinarily small degree of native or antecedent ionization

*C. T. R. Wilson, Sci. Abs. No. 849, 1901.

†Radioactivity and Geology, 1909 edition p. 192, by J. Joly, F. R. S.

with which to begin the action. It may hardly be said that ionization by impact is absolutely necessary in corona formation; in laboratory experiments, particularly at low barometric pressures and with the aid of a strong source of antecedent ionization such as ultra-violet light, X-rays, *et cetera*, corona can be produced with practically little or no antecedent ionization. However, under practical conditions where there is no artificial antecedent ionization corona can be started at the positive electrode *only by incoming negative ions* driven at ionizing velocity due to corresponding electric stress and at the negative electrode *only by out-going negative ions*, liberated by *impact* of incoming positive ions. Under practical conditions, therefore, no corona will form on electrodes of either sign without a natural source of ionization and none will be formed at the *negative electrode* without some source of negative ionization *at its actual surface*, or very near thereto. The known sources of negative ions at the surface of the cathode conductor are *impact* of incoming positive ions, *radioactive emanations*, *i.e.*, "dirt", captured by the cathode and near the surface, *collision* with neutral atoms of those few incoming positive ions that happen to find open a sufficiently long free path in which to attain ionizing velocity. Of these three, impact, emanation and collision, impact is of predominating importance. Emanation is ordinarily of far less importance, though when the conductors are generally covered with an active emanation, part-corona will start at a much lower voltage than the normal, *i.e.*, the Mershon critical voltage *at the cathode* will be much reduced. Collision is of doubtful extent and a small factor prior to the start of full corona.

It has been known for twenty years that the cathode when mounted in an attenuated gas and a high voltage applied to it will emit cathode rays only when the canal rays are allowed to impinge upon it.* In modern terms, it was found that the positive ions when driven against the face of the cathode by the electric field will cause it to emit electrons. Owing to the size the positive ions in a strong electric field move much more slowly among the atoms than the electrons; they rarely find free paths long enough to acquire ionizing-velocity; their movements can not be traced by resulting luminosity as is the case with the electrons.

*Schuster, Proc. Roy, Soc. xlvii p. 557, 1890. Results employed by J. J. Thompson in "Conduction of Electricity through Gases." First Edition, p. 383 and 384.

On account of the fact that this form of ionization is an important factor in corona formation a very limited first hand study of it was made as follows: Referring to Fig. 20, a pair of concentric cylindrical electrodes were mounted under the glass bell-jar of a laboratory vacuum pump. The dimensions of these electrodes are given on the inner pair of cylinders, Fig. 5. The air was exhausted to a pressure of about 3 in. (7.6 cm.) of mercury. A limited alternating 60-cycle discharge was then established between the cylinders by applying the high-voltage through a column of tap water contained in a glass U-tube. The discharge could be conveniently observed from the top. In Fig. 20 there is a reproduction of the sketch that was made by hand

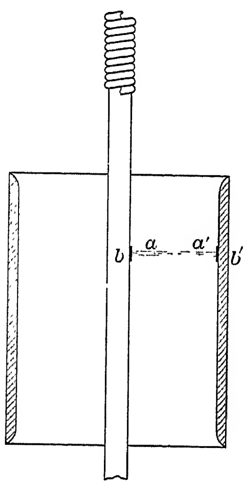


FIG. 20

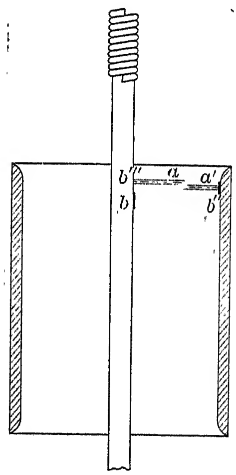


FIG. 21

while observing the discharge. The discharge would assume different appearances and positions. Examples of these are sketched in Figs. 20, 21, 22 and 23. Fig. 24, *a* and *b* are views from the top and side through a synchronous stroboscope. Fig. 25 is a top view through a revolving mirror. When using the stroboscope, an alternating arc operated from the same source as the high-tension circuit, was mounted and dimmed so that with the aid of a mirror, it and the discharge could be observed through the stroboscope together without changing the position of the observers eye. The instrument could be conveniently adjusted by hand for instantaneous observation at any desired phase as in Fig. 24*a* and 24*b* and 180 degrees remote

therefrom when the brush *a* and the spot *b* had exchanged places and for observations at all intermediate phases. Thus with the aid of the bright positive carbon of the arc and a carefully checked knowledge of the connections the cold bright luminescent spot, *b*, was observed to be located on the surface of the *cathode* and the yellow-violet *brush* was found to extend from the *anode*.

The somewhat attenuated atmosphere at a barometric pressure of about 3 in. (7.6 cm.) of mercury affords conditions that are favorable for bunching the travel of positive as well as negative ions. The magnetic-mechanic forces play the same role of a contractile envelope for both classes of ions. Under most

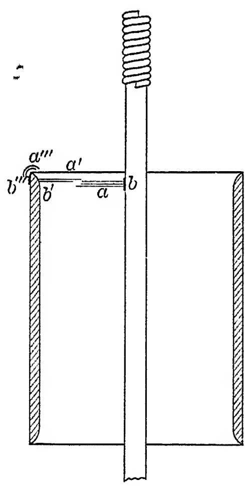


FIG. 22

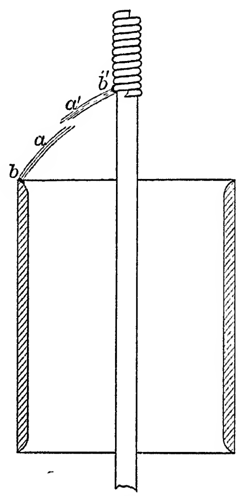


FIG. 23

circumstances as already stated the negative ions are the tiny active electrons while the positive ions are never smaller than the single atom and correspondingly less active. The consequence is that conditions which readily drive the one kind into cores will drive the other into diffusion and *vice versa*. In these experiments the density of the air was so adjusted that both classes of ions were driven into cores.

With the general knowledge of these matters in mind when viewing such discharges through the revolving mirror, Fig. 25, the phenomena of the discharge are easily traced to basic facts and principles. Through the mirror the cold bright luminescent spot, *b*, on the surface of the cathode is drawn out into a band

having no thickness; it is flat upon the surface of the conductor. Correspondingly the brush, *a*, attached to the anode is drawn out into a sine wave form solidly illuminated by the same yellow-violet glow. It appears like a colored trace of some sine-form alternation. The cold-bright cathode spot, *b*, is the light that is produced in the process of *intensive ionization by impact* of canal rays, *i.e.*, the incoming core of positive ions being driven by the field and cored mechanically by being forced into the route of least resistance and magnetically on the principle that each traveling ion has its equivalent in a tiny conductor carrying current and that like conductor-currents attract one another. The yellow-violet brush, *a*, is a luminosity that accompanies a fully matured process of ionization by the collision

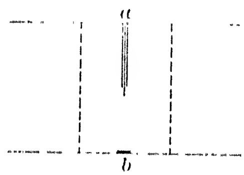


FIG. 24*a*

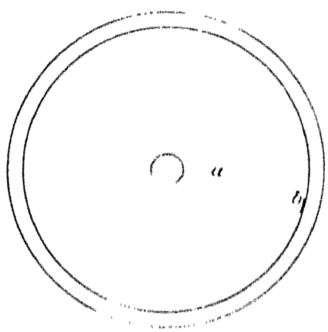


FIG. 24*b*

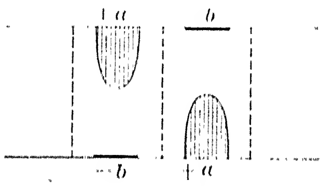


FIG. 25

of the negative ions, electrons, in this case and neutral atoms. The electrons that are detached by impact at the cathode are expelled from the cathode at ionizing stress by forming new atoms by collision as they proceed. Toward the crest of the voltage wave the process attains general ionization starting the brush just as the electrons strike the surface of the anode; at higher voltage the process culminates earlier, *i.e.*, at a shorter striking distance from the cathode and at a greater distance from the anode, producing a taller brush. In this way the brush constitutes a kind of a glow oscillograph for the top portion of the voltage wave.

Returning to the Figs. 20–23 series. These are sketches of the discharge as it appeared to the unaided eye in four typical

positions. After the use of the stroboscope and the revolving mirror it is easy to understand what is going on by direct view. The discharges sketched in Fig. 20 used a common route for both positive and negative ions. The electrons travel easily between the larger positive ions. Mechanically the streams, though opposite, interfere but little; magnetically they possess a common contractile envelope that cores them together in the same space. In Fig. 21 the mechanical and electrostatic interference of the two streams has caused them to core up in part along separate routes. In Fig. 22 the same general class of causes produced an interesting result. The positive ions missed the top edge of the outer electrode through the thermal, mechanical and electrical interference and struck the cathode from the rear by the in-draught of the electric field in that region. It is further of great interest to note that on the "return stroke" when this electrode was the anode that some of the arriving electrons followed the same route producing the luminosity lines curving over the rim of the cylinder to the spot where, in the preceding alternation, positive ions had been striking.

The concentric electrode cylinders in these experiments were mounted in the vertical. The discharges would invariably strike near the middle and drift spirally upward and lodge permanently in the position sketched in Fig. 23. In this position the negative and positive ions employed the same landing spots. Due to the fact that the electron core develops far more heat toward the end that has developed luminous ionization by collision, the buoyancy of that end is the greater. Because of lack of symmetry in respect to buoyancy when the luminous portion of the electron core on the return stroke strikes the copper wire wound about the top end of the central brass cylinders it is carried slightly higher than when it strikes the top edge of the outer cylinder quite exactly as sketched in Fig. 23.

The further evidence in regard to ionization by impact is not nearly so complete as it should be. Much of it is indirect in character. Physicists have studied the phenomenon only as occurring at the cathode whence the resulting electrons are expelled in a field sufficiently strong to ionize by collision.

There is no *direct* evidence that positive ions are produced at the anode by the impact of incoming negative ions or electrons. Likewise there does not appear to be anything known of the limiting stress below which ionization by impact will not occur at the cathode. There is much indirect evidence that this

class of ionization is produced abundantly only at stresses that are comparable with that required for ionization by collision. The same class of evidence indicates that at much lower stresses ionization by impact continues to occur but to a far smaller extent. The evidence shows that at the lower stresses, *i.e.*, 0.1 to 0.01 of critical collision stress, a very few of the incoming positive ions at the cathode produce negative ions by impact; most of them simply discharge and wander off as neutral atoms.

About a transmission line some ionization by impact begins at voltages that are as low as a tenth of those that produce the first traces of corona. The in-phase line charging currents ob-

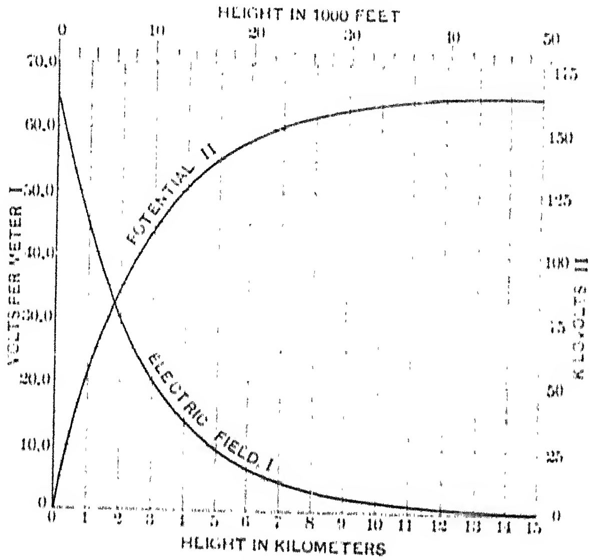


FIG. 26

served below critical voltage by Mershon at Telluride and Niagara Falls, by Smith at Worcester and West on the Shoshone-Denver 100-kilovolt high-altitude line are carried by incoming natural ions kept alive by impact. Not all are thus kept alive and some are lost by *recombination*. The stock of natural ions about a transmission line, operated below critical voltage, is augmented by natural ionization in the air and by radioactive emanations adhering to the conductors and maintained by impact until the rate of recombination equals that of supply. With increase of voltage the effect of the field is to entrain natural ions in larger numbers; all the ions migrate faster so

that the in-phase current thus carried as found by Mershon at Niagara, increases approximately as the voltage and the corresponding loss as the square of the voltage. In any event the amount of this loss is small compared with that produced by the inphase current carried by the ions formed in a fully developed and extended corona; it is entirely comparable in magnitude with the loss caused by part-corona.

That a high-tension transmission line does capture and operate as current carriers the native ions that are formed in its neighborhood, must be true because almost no ions can be found near such a line when in operation. Houllivigne "concludes from his experiments that very close to the wires there are sensibly no ions".*

He had undertaken to determine the part that a particular 50-kilovolt transmission line may play in the local meteorology. "Very close to the wires" means as close as the sampling apparatus could be mounted—probably not within a couple of feet.

Increase in frequency greatly facilitates ionization by impact and enables a high-tension transmission line to entrain and operate a larger number of natural ions. The lowest frequency at a given voltage is a corresponding continuous electromotive force. A continuous sub-critical high voltage applied to parallel clean conductors in the open sets up through the air an extremely small diffusion current—so small that it does not appear to be in the class of inphase diffusion currents as were found in the Telluride, Worcester, Niagara, and Glenwood-Denver sub-critical alternating high-voltage atmosphere loss tests.† With sub-critical continuous high-voltage the native ions actually migrate from cathode to anode and *vice versa*. All portions of the field traversed are very weak except those quite near the conductors. The velocity of the ions is, therefore, very slow and the opportunity for recombination correspondingly great. The result is that an early limit is set for the total stock of

*L. Houllivigne, "Ionization of Air by High-tension Overhead Wires." Comtes Rendus, 148 pp. 1668–1670, June 21, 1909. Quoted from Sci. Abs. No. 1430 p. 480, 1909.

† Mershon: TRANSACTIONS A. I. E. E., Vol. XV, p. 545.

Mershon: TRANSACTIONS A. I. E. E., Vol. XXVII, pp.864–881.

Worcester Poly. Inst. E. E. Dept., Thesis under direction of Harold B. Smith, 1901.

West: Tests of Glenwood-Dillon-Denver-Boulder 100-kilovolt 181-mile Transmission Line, July and Nov. 1909. (See current A.I.E.E. TRANSACTIONS, p. 77.)

entrained ions that are shuttled to and fro by the high-voltage field. An abundant recombination disposes of the additions from natural sources.

With sub-critical alternating voltages the ions do not have time to migrate from one conductor to another. About the cathode conductor during a positive high-voltage alternation the negative ions are expelled through the tubes of the electrostatic field, Fig. 27, *a portion of the way* to the anode conductor, and the positive ions are correspondingly drawn in a certain distance; during the next alternation the field is reversed and the ions make a corresponding return journey. Through a com-

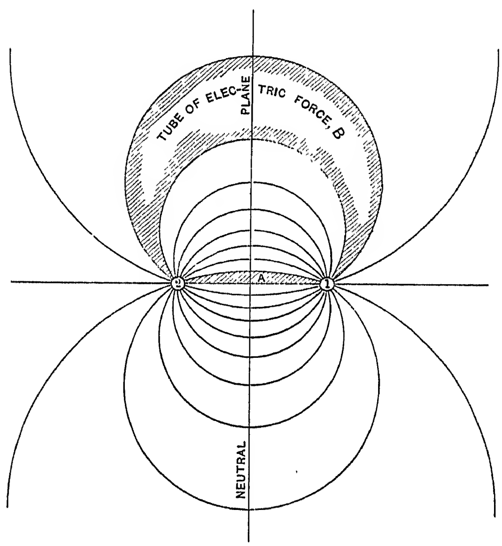


FIG. 27

bination of factors the ions will make a somewhat greater distance when travelling inward through a contracting electric tube of force than correspondingly outward through an expanding tube. The consequence is sooner or later that all ions that are repelled at one alternation will return in the first half of the next to strike the conductor surface reverse sign and retreat under expulsion before the close of the alternation and the beginning of the next.

This same state of things obtains at the other conductor. Each conductor is enclosed by a zone having a depth of a few inches within which the total stock of captured ions are actively

engaged in a *double frequency* synchronous advance and retreat. The *view* here presented seems to be the only one that corresponds to all the evidence that has so far accumulated in regard to the in-phase loss current set up at sub-critical voltage. A close study of Mershon's Niagara results develops the facts that the loss produced by this current varies approximately as the square of the voltage and *as the square of the frequency*; that such loss is largely independent of the size of the conductors, their distance apart and whether they are solid or stranded. These results show clearly that stranding lowers the critical voltage because it lowers the tendency of the outgoing electrons at the cathode to core-up and make an early part-corona start by the process repeatedly referred to in this paper, but they do not indicate that stranding lessens the loss current below the critical voltage that starts part-corona.

Change in voltage wave-form is a factor related only to critical and corona voltages and not to the amount of the loss below critical voltage. Remembering the evidence that has been presented which shows that an increase in antecedent ionization, *i.e.*, an increase in the loss at sub-critical voltage increases the strength of the contractile envelopes about the migrating ions and their ability to start brushes or part-corona and thus to lower the critical voltage and remembering also what has just been said above in regard to the factors that control and develop antecedent ionization: It is clear that an *increase in high-voltage as such* irrespective of stress factors, *i.e.*, the diameters and distances apart of the conductors, will relatively lower the critical voltage. This is the chief reason why Mershon's Telluride and Niagara results, as to his designation of critical voltage, differ so much after due allowance was made for change in atmospheric density due to altitude. The differences are due entirely to natural causes. The antecedent ionization in both cases are much the same at the same voltage. However, owing to the low barometer at Telluride the full corona starting voltage there, was but about *two-thirds* of the corresponding voltage at Niagara. The consequence is that the antecedent ionization loss at such voltage was only about *one-quarter* of the corresponding loss at Niagara, thereby elevating the critical voltage because the downward extent of the part-corona range was lessened.

e. Stranding and hard-drawing as factors that determine critical voltage and corona voltage.

In his Niagara Falls tests Mershon found that stranding the

conductors in a given case raises the critical voltage quite appreciably above that of the same corresponding case wherein the conductors are solid having the same *over-all* diameter. He found also that the critical voltage is increased as the number of strands is increased when the same over-all diameters are retained beginning with seven strands at which no increase occurred.

This effect is undoubtedly due to the fact that any change in the electric field within the small corona striking distance from the conductor surface will cause a corresponding change in the critical voltage that starts part-corona. Part-corona starts at the same critical collision-ionizing stress as that required to start uniform corona, the difference being that in spots more or less regularly distributed over the surface of the conductor the field has been concentrated at sub-corona voltages to the critical stress density, starting corona at such spots and giving rise to the phenomenon of part-corona or brush discharge already often referred to. This field concentration has been brought about by the concentrated travel of ions forming cores that act as conductors to concentrate upon them the electric field and to deplete it elsewhere near the conductors.

The aggregate effect of increasing the strands in a conductor is to expand the electric stress in the thin but important corona-striking envelope of air covering the conductors and to make the effect of such expansion amount to more than the effect due the resulting increase in capacity caused by the stranding.

In the same series of high-voltage tests Mershon also found correspondingly that the effect of " hard drawing " is to increase the critical voltage. By hard drawing the atoms of the conductor are made to take up a more compact arrangement—particularly at the surface. One must expect this to interfere with the ease with which the free ions of the conductor can act their part in the process of ionization by impact. If this view is correct hard drawing raises the critical voltage by failing to maintain fully the stock of ions that carry the in-phase loss current set up at sub-critical voltages, upon the inverse magnitude of which, as shown above, the critical voltage, among other factors, depends.

f. Quantity of antecedent ionization a critical voltage factor. This factor has been segregated by the application of first principles and by the study of a considerable range of high-voltage tests. In the final round-up of all controlling factors that

could be found it has taken a very important place. It was desirable, therefore, to obtain evidence by some convenient form of high-voltage laboratory experiment that would determine its existence in a manner as direct as possible.

The following experiment was chosen for this purpose. A diagram of the apparatus and its arrangement as employed in the experiment is given in Fig. 28. In a large open laboratory building a pair of tinned steel telephone wires, approximately No. 12 B. & S. gauge, were mounted and insulated for high-voltage tests, approximately 13 in. (33 cm.) between centers, making a line about 50 ft. (15 m.) long, 12 ft. (3.6 m.) from the floor. These wires had been in service and exposed to the weather for a year or more. Their surfaces had captured and retained comparatively little radioactive emanations as one familiar with such matters could tell by watching the manner in which part-corona first made its appearance. The wires were

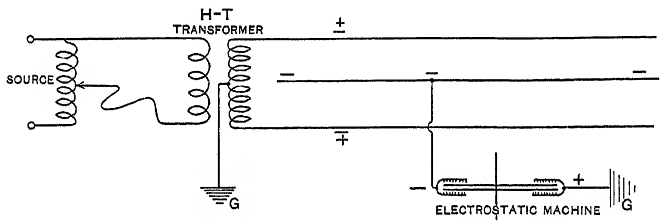


FIG. 28

therefore in a suitable condition for the purpose of the experiment. The actual critical loss-voltage value observed visually, was 58 kilovolts (effective sine-wave), 60 cycles. The previous use of the electrostatic cathode ray power diagram indicator had demonstrated that Mershon's value of critical voltage occurs at the first visual appearance of the part-corona brushes. Visual observation could therefore be relied upon fully for the purposes of the experiment.

In the plane of the conductors and midway between them a No. 30 B. & S. gauge bare copper wire was suspended and insulated for the application of high-voltage. It was connected to the negative terminal of an electrostatic machine, the positive terminal of which was grounded, as was also the middle of the high-tension transformer secondary. This electrostatic machine delivered to the wire about 0.00003 ampere at 10,000 volts. When no alternating high-voltage was applied to the line and

corona was produced over the fine wire by operating the electrostatic machine on the application of the alternating high-voltage to the line, the corona on the fine wire disappeared; the discharge from it was then entirely dark. With negative discharge on the fine wire absent, a critical voltage of 58 kilovolts (effective sine-wave) was required to start the first small brushes; on elevating the voltage full corona appeared *promptly*. With the negative discharge on the fine wire present, the corresponding critical voltage was only 52 kilovolts; on elevating the voltage full corona developed much more *slowly* than it did with the discharge on the fine wire absent. One could set the voltage on the line at 53 kilovolts with no evidence of part-corona formation as long as the fine wire discharge was absent. Immediately on starting the fine wire discharge, the first stage of part-corona appeared. The experiment was varied by setting the line voltage just under the normal critical voltage, *i. e.*, at about 57 kilovolts with the fine wire uncharged; immediately on charging the fine wire by starting up the electrostatic machine, a heavy part-corona approximating the stage of full corona appeared.

The experiment demonstrated that an abundance of negative ions produced in the neighborhood of a high-voltage line will lower the Mershon critical voltage materially while it will change but little the voltage that develops full corona. Of itself an experiment of this sort would not amount to much; considered in connection with the fact that the critical voltage is lowered as the in-phase ionization current increases, it occupies a place of real value as a check upon ones understanding of these matters.

g. Captured emanation or " dirt " on the conductors as a critical voltage factor at the cathode only; resulting effects in corona formation by continuous and alternating high-voltages.

Mershon, Watson*, Whitehead† and others have found that dirt on the conductors will lower the critical voltage. Mershon and Whitehead used alternating voltages; the former employed parallel conductors in the open, the latter, closed concentric cylinders. The results of both agree and show that the effect of dirt on the conductors is to lower the critical voltage; White-

*E. A. Watson, " Losses off Transmission Lines Due to Brush Discharge with Special Reference to the Case of the Direct Current." British Assn. Advancement of Sc. Winnipeg 1909 meeting advance copy. E. A. Watson " Atmospheric Losses from Wires under Continuous Electric Pressure." *Electrician* Sept. 3. 1909 and Feb. 11 and 18, 1910.

†J. B. Whitehead, "The Electric Strength of Air." See TRANSACTIONS, A. I. E. E.. Vol. XXIX, p. 1159, 1910.

head concludes that it may be lowered as much as 33 per cent. Watson, using closed concentric cylinders and continuous high-voltages found in the particular test of dirty wire reported in his Winnipeg paper that the critical *negative* voltage was lowered as much as 50 per cent. He gives voltage current loss curves for the wire dirty and clean, showing that the dirt lowers the critical corona by concentrating the stress and starting part-corona at lower voltages than those required to start uniform corona on clean wires. When the conductor was subjected to positive, in lieu of negative continuous potential, dirt on its surface had little or no observable effect upon the value of the critical voltage and loss current set up when such voltage was exceeded.

There are two classes of "dirt" to be considered in this connection: (1) the one made up of very fine conducting material such as precipitated carbon and (2) the other, made up of non-conducting or partially non-conducting material, rich ionized molecules or particles, or radioactive emanations that are so easily captured from the atmosphere. It was known in advance that the second class of dirt would, when adhering to the surface of the cathode-conductor, become radioactive under the negative high-voltage stress and emit negative ions and therefore electrons that promptly become detached from such ions under great electric stress and thus concentrate the field over such patches of dirt starting thereat part corona at a lowered critical voltage.

There was, however, some doubt as to the behavior in this respect of dirt of the first class. The electrostatic power diagram indicator was, therefore, applied to a pair of parallel piano wires mounted at the centers of their enclosing cylinders and the 60-cycle alternating high-voltage noted that started the formation of a power card. This done the wires were coated each with a thin layer of fine carbon deposited from the flame of a candle mounted underneath by a wire carrier to which was attached a string and drawn forward slowly from end to end of each wire. The experiment was again repeated and it was found that the critical voltage had been increased from 22 to 24 kilovolts, evidently due to the effective increase in the diameter of the wire made by the envelope of fine conducting carbon. This result was accepted as satisfactory proof that dirt which is almost wholly made up of fine conducting material, *i.e.*, dirt of the first class, is not a factor in lowering the critical voltage.

A corona voltmeter was made by mounting a clean tapered

brass conductor at the center of a cylinder of half-inch (12.7-mm.) mesh wire screen.* It is used for observing transient voltage. It stands in the open laboratory and after a time the surface of the brass rod must be cleaned to remove the captured emanations that cause its corona performance to be irregular. When it has not been cleaned for a time stout brushes appear at various places on the rod where there should be no corona. These brushes will always adhere to particular spots which when examined in the full daylight frequently can be hardly distinguished from the normal surface of the rod. The spots locate the presence of radioactive emanations that are easily removed mechanically. Once started they become centers about which preferential capture continues because of their own contribution to the electric field about the rod.

Doubtless all manner of dirt of the above second class will behave as these emanations behave because of the abundant ions that such material contains. In general the effect upon the alternating critical voltage and in-phase loss currents at higher voltages is much the same as that which is produced by the loss currents due to the stock of ions captured at sub-critical voltage. There are, however, no frequency and absolute potential factors connected with effects due to captured emanations and dirt as is the case with ions that are captured and held to cyclic orbits in the atmosphere about the conductors.

h. Form of the electrodes and resulting figure of the electric field as critical voltage and corona formation factors.

There are three classes of electrodes to be considered in this connection:

1. Concentric cylinders.
2. Small cylinder and plate—parallel mounted.
3. Small parallel cylinders.

The first two are used only for laboratory purposes. The concentric cylinders have been much used for the laboratory study of corona. By their use corona is developed only over the small central cylinder in the envelope of air immediately adjacent thereto which is subject to a uniform spreading stress in an amount that is exactly calculated from the dimensions. The high-voltage required to produce corona-forming stress is one-half or less than that which is required when wires or cables are used. Thus with a 125-kilovolt source, as great balanced

*Harris J. Ryan. Discussion giving details of this instrument. TRANSACTIONS A. I. E. E., XXVIII, II, p. 804, 1909.

stresses in the air about a conductor at the center of a cylinder can be produced as when 250 kilovolts are employed to stress the air covering a pair of conductors of the same size mounted parallel and at a suitable distance between centers.

Owing to the lower absolute potentials and the very small volumes of open air from which to capture a stock of ions, due to the facts and principles already established, the ionic loss currents at sub-critical voltages are exceedingly small; they can be detected only by the most delicate means. It is assumed that the high-voltage employed is alternating. The currents are too small to concentrate the field and start brushes at stresses lower than the one that will strike full corona; at all events nearly so. For the corresponding line of parallel wires or cables, to which is applied high-voltage in the open, this native ionization current would invariably be ample to concentrate the stress and thereby to lower the critical voltage. With concentric cylinders this antecedent ionization current is so small that it has little or no effect upon the critical voltage. There is practically no *part-corona range* and initial and corona voltages are not to be distinguished except possibly for the larger sizes of conductors *i.e.*, upwards from 0.3-in. (7.6-mm.) diameters.

The vapor-product in this form of high-voltage atmosphere loss-test can not be a critical voltage factor. The vapor-product is a critical voltage gauge only when the water vapor put into the atmosphere has been subject to a definite and rather abundant antecedent ionization, natural or artificial. The vapor-product will be discussed briefly as a separate topic. The results reported to the Institute by the author in 1904, already referred to, so far as they go, confirm these characteristics of the concentric cylinder tests.

Whitehead employed closed concentric cylinders, 60-cycle alternating high-voltage, central conductors of various diameters. From enclosed atmospheres at different temperatures, laden with moisture in known amounts over a wide range, he obtained results in abundant confirmation of the above understanding of the character of corona formation that is produced with concentric cylinders. Inherently, this method causes critical and full-corona voltages to be almost identical. In fact it practically eliminates the turbulent critical alternating voltage control factors contributed by the atmosphere in the open; the aggregate effects of these factors culminate in the behavior of the captured stock of natural ions whereby as already stated the elec-

tric field close to the wire is greatly disturbed, and concentrated in spots to such an extent as thereat to start part-corona and therefore to attain critical voltage at lower, and in some cases much lower, than the voltages required to produce full corona in the undisturbed electric field.

The concentric cylinder method constitutes a laboratory expedient wherewith to investigate the basic phenomenon in the corona problem, *viz.*, corona formation under known conditions as to figure of field and electric stresses. It eliminates all the disturbing factors that occur under practical conditions. It is purely a technical expedient for segregating and determining the character of the basic phenomena in corona formation under definite and decidedly limited conditions. The results that the method gives are an important aid to the *judgment* but are not to be employed for practical purposes without a knowledge of the *factor of safety* that must be applied to include the many turbulent, modifying elements that enter to determine critical voltage, part-corona range, and the ultimate culmination of full corona. This factor of safety is somewhat analogous to that which is employed in mechanical problems to include the turbulent elements that are inherent under practical mechanical conditions but which can not be given a rigid treatment as can the basic portion of the problem.

The position that the concentric cylinder corona test occupies should not be left without a further reference to the work of Watson who employed continuous high-voltages in this method. He found substantially the same critical voltage stresses at the surfaces of the wires that were found by Whitehead and the author using alternating high-voltages. His critical and full corona starting voltages were likewise coincident. His results confirm positively the conclusion drawn from fundamental facts and principles that corona formation, as such, is entirely independent of the frequency; they confirm likewise the conclusion that the concentric cylinder test determines corona formation under strictly definite and limited conditions as to amount of antecedent ionization and distribution of electric strain in the air about the conductor.

Watson's Winnipeg paper includes excellent photographs of the positive and negative coronas formed by continuous high voltages. The positive corona is uniform and flat against the surface of the conductor while the negative corona is irregular and lies more distant from the surface of its conductor. All

this is quite as it should be in the light of first principles. The positive corona is formed by collision-ionization, due mostly to incoming electrons, that culminates in the air right next to the anode-conductor surface when the critical voltage has been exceeded. The negative corona is correspondingly due to collision-ionization produced also by electrons that are being expelled from the surface of the cathode-conductor where they have been liberated by the impact of incoming positive ions and by captured emanations; it culminates initially, not at the surface of the conductor but radially remote therefrom at *the corona striking distance.* The extra irregularity of the negative corona is due to the captured emanations which through their radioactivity concentrate the field about them, thereby lowering the critical voltage and forming a part-corona range at the cathode conductor, just as is the case correspondingly at both conductors when " dirty " and alternating critical high-voltages are applied.

Herein lie all the causes for the radical difference in the corona behaviors at anode and cathode in relation to critical voltage, part-corona range and initial full corona as modified by the presence on their surfaces of captured emanations and ionized " dirt ".

Moody and Faccioli employed the small cylinder and plate, parallel mounted, in their corona investigations reported to the Institute in 1909, reference to which was made earlier in this paper. Their corona tests were made in a small in-door enclosure securing thereby daytime darkness to permit visual observation of initial corona voltages. These voltages are *critical corona voltages* and not *critical loss voltages* and as such are comparable with the critical corona voltages observed by Whitehead and the author. They employed a 60-cycle 100 kilovolt (effective sine-wave) current. The small cylinder was connected to one terminal of the transformer, the remaining terminal of the transformer and the plate were grounded. Nothing is said in the paper apparently, in regard to the potential of the transformer case. In Fig. 2 of their paper the high-tension transformer employed is represented as mounted on the " floor ", uninsulated and quite near the test rod and plate. The conductivity of the floor under the circumstances is a considerable factor in determining the absolute alternating potential to which the air would be subjected in which the test rod is immersed.

With small conductor sizes having diameters near *one-eighth* inch (3.17 mm.) they found critical corona voltages sharply de-

fined that are in agreement as to electric stress with the Whitehead and author's values obtained from concentric cylinders. With larger conductors they found critical corona voltages that were relatively higher. For a conductor having a diameter of *one-half* inch (12.7 mm.) with its center 18 in. (45.6 cm.) from the surface of the plate the critical corona voltage found was 95 kilovolts (effective sine-wave), while the corresponding value given by the author's formula as calculated by Moody and Faccioli is 83 kilovolts. This formula gives critical corona voltages that occur in the use of the concentric cylinders. When the distances between the conductor and plate is less the observed values are relatively higher than the calculated value.

Because the figure of the field in this case is considered to be quite exactly the same as that set up from one conductor to the "neutral plane" for the case of two parallel cylinder-conductors; because the field is in the aggregate much less regular than the field between the corresponding concentric cylinders; and again because the whole arrangement is apparently much more open than the concentric cylinders closed or open, it was at first surprising that this method should give critical corona voltages which are decidedly higher than those given by the concentric cylinders. Particularly is this so for the larger diameters whereat the field in the corona striking zone next the conductor surface also begins to be unbalanced partaking of the general character of the field. The observed and calculated values, using the authors formula for the latter, as obtained by Moody and Faccioli in these experiments are taken from page 774, Fig. 3, and page 775 of their paper and tabulated below:

DIAMETERS OF CONDUCTORS IN INCHES

	0.125	0.125	0.25	0.25	0.375	0.375	0.50	0.50
Distance	Kilo-volts	Kilo-volts	Kilo-volts	Kilo-volts	Kilo-volts	Kilo-volts	Kilo-volts	Kilo-volts
inches	obs.	calc.	obs.	calc.	obs.	calc.	obs.	calc.
9	36.5	38.3	55.0	50.5	70.0	61.2	85.0	71.5
12	37.5	40.5	58.5	53.5	76.0	65.0	90.0	76.5
18	42.0	43.0	62.0	57.7	81.0	70.3	95.0	83.5

The calculated values for the *one-eighth* inch (3.17 mm.) conductor were added by the present author using the new formula derived toward the close of this paper.

Moody and Faccioli followed up the causes of these discrepancies by undertaking many interesting and instructive

experiments. In one set of such experiments they used concentric cylinders open ended. The inner radius and length of the outer cylinders were 5 in. (12.7 cm.) and 18 in. (45.6 cm.). The test conductor was mounted at the center of this cylinder and connected as always to one terminal of the high-tension transformer, the other terminal and outer cylinder were grounded. The values observed herewith and those correspondingly calculated by the present author using his later formula are given in the following table:

Diameter inch.	Observed by Moody and Faccioli Kilovolts*	Calculated by the author Kilovolts*
0.125	24.0	30.2
0.250	36.5	38.5
0.370	47.5	45.3
0.500	54.5	51.6

*Effective, sine-wave potential.

If diameter critical corona voltage curves were located with these values they would intersect. These results show conclusively that the air inside the cylinder was subjected to a composite electric stress due to the potential difference between the cylinders and the absolute potential of the air in which the open cylinders were immersed. An erratic migration of ions occurred causing corresponding changes in the normal ionization of the air within the outer cylinder and in the stresses that strike corona adjacent to the conductor surfaces.

(1) In the concentric cylinder tests of Watson, Whitehead and the author the air between the cylinders was not subject to disturbances by contact with an outer atmosphere at an uncertain potential, and the critical corona stress results are in remarkable agreement although the construction and methods in most other respects differed greatly. (2) When we undertook critical-loss voltage tests on a three-phase high-tension laboratory line charged from two open delta-connected 20-kw., 60-kilovolt 60-cycle transformers, although the three alternating potential differences were practically balanced as to phase and voltage, the resulting corona formation was remarkably unbalanced because of the disturbances of the neutral potentials caused by the electrostatic relation of the transformer cases, high-voltage circuits, three-phase line, "ground" and surrounding atmosphere.

This can probably be overcome by resistance loads properly applied; time has not as yet permitted this to be tried out.

These two sets of evidence together with the general principles involved demonstrate conclusively the cause of the erratic corona behavior found in the above tests using the rod and plate. It is doubtless possible to shield the rod and plate electrode from uncertain potential interferences with the stresses and migrating ions, in which event the Moody-Faccioli evidence indicates that this form of test will yield much the same critical corona stresses as those obtained by the use of the concentric cylinders with the surrounding normal zero potential undisturbed. In any event the parallel rod and plate, while offering greater structural and experimental convenience, can not employ on the one hand such a definite limited stock of natural ions as the concentric cylinders, while on the other hand it does not nclude all of the factors that enter when the parallel cylinders are used in the open so as to obtain critical loss and critical corona voltage corresponding to the conditions of practical operation.

The factors that enter when the electrodes are parallel cylinders mounted in the open atmosphere, indoors or out according to the kind of air to be studied, have already been considered. Some special examples will be considered below as a separate section of the paper. This is the only form of test that yields the composite results that are applicable to practice.

i. The power transmission current as a possible critical voltage factor.

The magnetic field set up about the transmission conductors in concentric zones of maximum strength at the surface of the conductor will have some influence in determining the value of the critical loss voltage. There is abundant evidence that anything which alters or disturbs the normal movements of the electrons very near to the surface of the conductors will modify the critical loss voltage. Electrons, when driven through a magnetic field, are everywhere turned at right angles to the direction of the field. The actual directions are the same as for the deflections of equivalent currents. The field that the power current sets up will cause the electrons to be forced out or drawn in by curvelinear routes near the surfaces of the conductor. From the general nature of the phenomena one must expect that this cause will effect a certain increase in the critical loss voltage —perhaps comparable with that caused by stranding the conductors.

j. The vapor-product as a critical loss voltage factor found by Mershon at Niagara Falls.

When one considers the evidences that establish the place that natural ionization occupies in determining the extent and character of the energy loss in the atmosphere about high-voltage transmission lines; when it is remembered that the vapors rising from great water falls are highly ionized; and when the fact is included that artificial changes in the vapor product unaccompanied by corresponding ionization changes cause little or no change in critical loss voltages one is forced to conclude that the vapor-product at Niagara Falls was a pretty good gauge of an extra natural supply of ions that were carried to the region of test by the vapors rising from the near-by falls. One must, therefore, expect to find the vapor-product acting the role of an ionization gauge in similar localities and along ocean shores, etc.

k. Absolute potential and phase relations as critical voltage factors. (Polyphases, balanced and unbalanced.)

It was expected in advance that a four-wire, two-phase line wherein the conductors are mounted at the corners of a square, each phase occupying a diagonal, would render critical loss and corona voltages identical with those rendered on one phase and the other cut-out. This was tried out and found to be so. When both phases are applied to the lines the instantaneous voltage of the one is zero when the other is maximum and engaging in corona formation, if the critical voltage has been exceeded. From first principles it was expected that each conductor held its captured stock of ions so close in as not to contribute to the effective stock of the other. The result of the experiment confirmed this understanding of the matter.

The conditions about a three-phase line are somewhat different in that only one conductor comes to maximum potential at a time, and for this reason it was expected in advance of actual trial that when any sort of unbalancing was present the individual conductors would have differing opportunities to capture a stock of ions. In advance of actual trial this feature was rather dimly realized from fundamentals. Our facilities afforded an adjustable three-phase 60-kilovolt, 60-cycle source only by means of two open-delta connected, 20-kw. transformers. The No. 12 B. & S. gauge tinned and weathered telephone wires were mounted for the application of high-voltages inside a large open monitor type laboratory building. The length of line was about 130 ft. (39.6 m.); the center to center separation of the

three conductors was 12.5 in. (30.5 cm.). The high voltage delivered from the open-delta-connected transformer secondaries was adjusted to a true three-phase condition at the voltage maxima both as to phases and magnitudes and then checked by needle spark-gap.

The transformer cases were thoroughly insulated by mounting the transformer on a frame supported by a bank of standard 30-kilovolt insulators. The terminals of the two transformers are designated 1 and 2′ and 2″ and 3 respectively. 2′ and 2″ were joined making a common terminal 2 so that the three-voltages were delivered from between 1, 2 and 3, in the usual fashion, to the line conductors correspondingly numbered 1, 2 and 3. The first set of observations were made by applying the high-voltage to the line with the transformer cases insulated. The voltage was gradually raised and the corresponding values noted at part-corona started on each line conductor. The results obtained were as follows:

TRANSFORMER CASES INSULATED

Conductor	Critical loss effective sine-wave kilovolts
1	33.6
2	49.6
3	29.2
	Single phase (2:3 cut out)
1:2	46.4

The test when repeated with the transformer cases grounded yielded the following results:

TRANSFORMER CASES GROUNDED

Conductors	Critical loss effective sine-wave kilovolts
1	35.6
2	50.2
3	32.0

The above test was then repeated one change only having been made, *viz.*, two of the three connections between the source and the line were reversed.

TRANSFORMER CASES GROUNDED
Leads 1 and 2 to line reversed

Conductors	Critical loss effective sine-wave kilovolts
1	46.0
2	33.6
3	28.8

These results bring out clearly the importance of the absolute alternating potential of the line conductors in relation to their potential differences. The few hurriedly made tests demonstrated promptly that to go into the matter fully would constitute a considerable undertaking. Work along this line had to be given up, therefore, for the time being, as the purpose of the present undertaking was to be strictly limited to an effort to secure some hold upon the fundamental facts and principles that have a general application in these matters.

In concluding this sub-topic attention is called to the relation of these results to those already referred to of Moody and Faccioli who also introduced the absolute potential factor by operating with one terminal of their high-voltage transformer grounded.

IV. Conclusions and Table of Corona Formation Data Obtained from High Voltage Line Tests

The fundamental feature of corona is the formation of a collision-ionization envelope about the conductors of the high-voltage transmission line. Under normal atmospheric conditions, *i.e.*, barometer 29.5 in. (750 mm.) of mercury and temperature 70 deg. fahr., the critical stress required to start collision ionization when regularly distributed, is 76 kilovolts per in. (30 kilovolts per cm.) at the critical striking distance, a, Fig. 2, from the surface of the conductor. It varies directly as the barometric pressure and inversely as the absolute temperature.

In addition to ionization by collision as the *basic factor* in corona formation, there is the complex and entirely turbulent *irregularity factor* that is made up for a given case, in whole or in part of the following elements, given approximately in the order of their importance:

1. Irregularity of electric fields beyond the atmospheric envelope covering the conductor in which the initial corona strikes.

2. Earth connection; on one side or at the neutral of the high-voltage source.

3. Excess or lack of natural or antecedent ionization of the atmosphere.

4. Captured ions and radioactive emanations at the conductor surfaces.

5. Mechanical form of the conductor surface affecting the uniformity of the electric field within the thin corona striking envelope covering the conductor.

6. Physical character of the conductor surface as to hardness and molecular structure that affect the impact ionization facility.

7. Magnetic fields about the conductors due to the power currents they transmit.

8. Stray factors, *viz.*, ultra-violet light, *et cetera*, none of which are important.

For convenience in referring to the parts of a corona voltage loss curve, the following terms are employed: It is assumed that the losses in watts are the ordinates to the curve and the voltages the corresponding abscissæ: That portion of the loss curve developed at voltages below the critcal voltage will be called the *lower part*, the succeeding portion covered by the sharp upward turn will be called the *elbow* and the remaining portion will be called the *upper part*. The losses expressed by the lower part, elbow and upper part are designated as losses by *convection*, *part-corona*, and *corona*, respectively.

The convection current is small and of little importance on its own account, except at very high voltages, high altitudes or high frequencies. However, the convection loss current interferes considerably with the regularity of distribution of the electric field very near the surfaces of the conductors a vital controlling factor in corona formation. The larger the convection current the greater is this effect of strengthening the field in spots at the surface of the conductor where part-corona will start at a correspondingly lower average stress and therefore line voltage. The character of the lower part of the corona loss curve is, therefore, of much indirect importance. The convection current increases with the amount of natural or antecedent ionization—at what rate is not yet definitely known; it also increases approximately as the altitude and as the square of the voltage and frequency.

The form of the elbow, *i.e.*, the changing rate at which part-

corona begins and merges into corona as the voltage is increased is directly related to the amount of the convection current. The larger the convection current in a given case the lower will be the corresponding critical voltage at which part-corona will start and the more gradual will be the rate at which such part-corona will turn into a full corona as the voltage is increased; *i.e.*, the steeper the lower part of the loss curve the longer the elbow.

The result in the aggregate is that, whereas critical voltages at which part-coronas begin are greatly and irregularly affected by these turbulent factors, such factors have a much smaller and more definite effect upon the voltage at which part-corona ceases and corona begins. Full corona formed about parallel transmission conductors in the open is never as regular as that which is formed about the small inner cylinder by laboratory test. The result is that corona begins on a transmission line at about 80 per cent of the corresponding corona voltage found by the concentric cylinders laboratory test. This factor applies to an ungrounded circuit and to round solid, or seven-strand conductors. Grounding the circuit may change this factor considerably, Smith's 1901 results show that a neutral ground may under some circumstances raise the value considerably while it is reasonable to expect in the light of all the available evidence that a high potential ground may lower it some. Stranding the conductors interferes with the concentration of the convection current at or near their surfaces. It increases the number of ion-cores or current streams and thus lessens the irregularity of the surface stress, raises correspondingly the critical voltage, lessens the part-corona range and in the end lowers the above irregularity corona factor; *i.e.*, for stranded conductors and a given pitch of the lower part of the loss curve the elbow is sharper and shorter and the upper part steeper compared with corresponding solid conductor results.

The elbows of the loss curves cover wide voltage ranges—from 5 to 50 per cent of the initial corona voltage. Owing to the fact that a long elbow is followed by a slow rise in the high-voltage loss curve and *vice versa* these variations are compensated to a considerable extent. An average of 10 per cent of the initial corona voltage may be taken for practical purposes to cover the length of the elbow under ordinary conditions.

Thus a rational formula in part for predicting critical and corona voltages may be derived by employing these factors as follows:

Let E_c be the critical corona voltage.

E_{pc} be the critical part-corona voltage.

E_{cc} be the critical corona voltage due to critical stress, critical striking distance and a given density of air; *i.e.*, the critical corona voltage obtained by laboratory test using concentric cylinders.

k_c be the *irregularity factor* for transmission line critical corona voltage, *i.e.*, $k_c = \frac{E_c}{E_{cc}}$.

k_{pc} be the part-corona factor, *i.e.*, $k_{pc} = \frac{E_{pc}}{E_c}$.

k be the irregularity factor for critical loss voltage; *i.e.*, $k = k_{pc}\, k_c$.

E_{crit} be the *crictical loss voltage.*

i.e.,

$$E_{crit} = k\, E_{cc} = k_{pc}\, k_c\, E_{cc}.$$

As stated above under all ordinary circumstances:

$$k_c = 0.8;\ k_{pc} = 0.9; \text{ and } k = 0.8 \times 0.9 = 0.72$$

i.e.,

$$E_{crit} = 0.72\, E_{cc}$$

This does not place the critical voltage as low as the exact value where convection loss transfers to part-corona. The convection loss is small; it is given approximately by the following equation:

$$P = 2.0 \times 10^{-6} f^2 E^2$$

wherein P = watts per 1000 feet, single phase line.

f = frequency.

E = kilovoltage.

Example: $f = 60$ $E = 100$. Substituting $P = 72$ watts, or 380 watts of convection current loss per mile of single-phase line.

The change from convection to part-corona loss is always very gradual. The entire part-corona range multiplies the inevitable high-voltage loss by convection *not more than five* times. The above ratio

$$\frac{E_{crit}}{E_c} = 0.9$$

places the critical voltage high enough so that part-corona has increased the loss by an amount approaching the corresponding convection loss at the same voltage. Where corona is the voltage limiting factor, a few part-corona brushes will cost less than the increased cost in transmission caused by lowering the voltage to a point where they are completely eliminated. The factor $k_{pc} = 0.7$ and therefore $k = 0.56$ would eliminate brush discharge completely but at too great a cost. For this reason $k_{pc} = 0.9$ is chosen as a typical value based on a convection and brush discharge or part-corona loss less than one kilowatt per mile of a 100 kilovolt transmission line for usual conditions as to ionization, low altitude, temperature, etc.

No consideration is made here of the effect of part-corona on the durability of the conductor. Matters of that sort are not herein considered.

The factors $k = k_c \, . \, k_{pc}$, should be chosen with the same care and judgment as are employed in the selection of safety factors for structural design where turbulent elements enter along with those of a definite fundamental character. The critical loss-voltage factor $k = 0.72$ *i.e.*, $k = k_{pc}\,k_c = 0.9 \times 0.8 = 0.72$ is perhaps as safe a factor as any to be used without the aid of a judgment experienced and trained in these matters.

The rational value of the initial uniform corona voltage, E_{cc}, employed above is derived as follows:

E_{cc} is that voltage which will establish critical stress factor in a zone about the conductor at a distance from its surface equal to the corona striking distance. The normal critical stress is 76 kilovolts per in. (30 kilovolts per cm.) and the normal critical striking distances, a, in relation to the conductor diameters are obtained from the curve in Fig. 2. The electrical stress at the surface of a transmission conductor in kilovolts per in. is the ratio of the capacity per square inch of the surface of such conductor to the capacity of an inch-cube of air—the latter being 2.244×10^{-13} farads, thus kilovolts per in. surface stress factor =

$$\frac{C \times 10^{-6}}{1000 \times 12 \times \pi \, d} \times \frac{1}{2.244 \times 10^{-13}} = \frac{10^3}{2.70 \, \pi} \quad \frac{C}{d}$$

wherein C = capacity of line in microfarads per 1000 feet.

d = diameter of conductor in inches.

The voltage that will produce a stress of 76 kilovolts per in. at the distance, a, from the conductor surface

$$E_{cc} = \frac{76}{\sqrt{2}} \cdot \frac{2.70\ \pi}{10^3} \cdot \frac{d+2\ a}{C}$$

$$E_{cc} = .455 \cdot \frac{d+2\ a}{C} = \qquad (1)$$

the kilovolts, (effective sine-wave) required to start *uniform* corona about cylindrical clean conductors in the normal atmosphere wherein the values of a, C and d are given as defined above.

The corresponding critical loss, kilovolts for all ordinary conditions are

$$E_{crit} = .328 \cdot \frac{d+2\ a}{C} \qquad (2)$$

The corresponding expression giving the critical loss-kilovolts for any set of conditions is

$$E_{crit} = .455 \cdot k \cdot \frac{17.9\ b}{459+t} \cdot \frac{d+2\ a}{C} \qquad (3)$$

wherein: E_{crit} = critical loss kilovolts, (effective sine-wave).
k = $k_{pc} \times k_c$, factors selected by judgment guided by the results of practical tests and experience.
d = outer diameter of wire or cable in inches.
a = corona striking distance obtained from curve in Fig. 2.
b = barometer, inches of mercury.
t = temperature, deg. fahr.

All available data relating to corona formation obtained from high-voltage line tests are given in the following tables. The values headed "Critical Uniform Corona Voltage, Calculated" were determined by means of the above equation, No. 3, omitting the factor, k. Fig. 29 is a reproduction of a photograph of the part-corona display on the 110-kilovolts transmission line in Michigan upon which the tests were made by Foote. Other items of interest connected with these data not subject to tabulation are given in footnotes.

TABLE I.

Number	Month, test	Year published	Name	Place	Altitude, feet	Barometer, inches	Temp. deg. fahr.	Conductors: Circuit: Length	Phases	Cycles	Section cms.	No. of strands	Diameter over all inches	c:c inches	Capacity m.f. per 1000 feet	Critical loss-voltage; kilovolts (effective sine-wave) observed	Critical corona voltage: kilovolts, Effective sine-wave observed	Critical uniform corona voltage kilovolts (effective sine-wave calculated§	k_c	k_{pc}	k	Remarks
1		1897	Mershon	Telluride, Col.	8,000	21.5†	60†	Feet 11,720	1	60	24,000	1	0.156	52	0.00131	54.0	56.0	73.6	0.76	0.96	0.73	In Rocky Mountains
2	2 p.m. May 14	1901*	Smith‡	Worcester		29.5	70†	250	1	60	10,400	1	0.102	30	0.00133	64.0	69.5	76.0	0.91	0.92	0.84	On Worcester Campus
3	May 28	1902*	" ‡	"		"†	75†	"	1	60	66,400	1	0.258	48	0.00143	95.0	107.0	123.5	0.86	0.89	0.76	" " "
4	May 29	1902*	" ‡	"		"†	75†	"	1	60	66,400	1	0.258	24	0.00162	107.0	123.0	109.0	1.13	0.87	0.98	" " "
5		1908	Mershon	Niagara Falls	660	29.5†	70†	1,000	1	73	10,500	1	0.102	55	0.00121	58.0	61.0	76.0	0.80	0.95	0.76	Vapor Product 0.2
6		"	"	"	"	"	70†	"	1	73	20,740	1	0.144	55	0.00128	77.0	81.0	96.5	0.84	0.95	0.80	" " "
7		"	"	"	"	"	70†	"	1	73	34,600	1	0.186	55	0.00133	80.0	86.0	105.5	0.81	0.93	0.76	" " "
8		"	"	"	"	"	"	"	1	73	41,800	19	0.234	55	0.00138	88.0	89.0	120.5	0.74	0.99	0.73	" " "
9		"	"	"	"	"	"	"	1	73	41,750	37	0.235	55	0.00138	90.0	90.5	121.0	0.75	0.99	0.74	" " "
10		"	"	"	"	"	"	"	1	73	42,910	7	0.235	55	0.00138	92.5	93.0	121.0	0.77	0.99	0.76	" " "
11		"	"	"	"	"	"	"	1	73	103,850	7	0.366	29	0.00168	Approximated 106.0	—	136.2	0.78	1.00	0.78	" " "
12		1910	West	Central Colorado Power Co's. Line: Glenwood, Dillon Denver and Boulder	11,500	18.2†	70†	181 Miles	3	60	83,690	6	0.354	124	0.00129	77.0	—	107.0	—	—	0.72	One transmission line; operating at 100 kilovolts.
12		"	"		13,300	16.5†	70†		3	60	105,500	6	0.398	124	0.00133	77.0	—	103.0	—	—	0.75	
13		"	Foote	Grand Rapids, Mich		29.5†	70†	50	3	60	66,370	6	0.316	96	0.00132	110.0	—	156.0	—	—	0.70	Operating at 110 kilovolts
14		"	"	Flint, Mich.		"	"	125	3	60	105,500	6†	0.398	120†	0.00132	135.0	—	184.0	—	—	0.73	135 kilovolts proposed
15		"*	Ryan	Stanford	100	30	70	Feet 130	1	60	7,210	1	0.085	12.5	0.00151	47.0	—	60.0	—	—	0.76	Test made in monitor type open laboratory building
16		"*	"	"	"	30	70	130	1	60	83,700	7	0.331	36	0.00157	106.0	—	135.0	—	—	0.76	

*Not published. †Assumed. ‡Middle of high-voltage transformer grounded. §Equation No. 3 used, omitting k.

TABLE II.

No.	Name and place	Loss by convection	Loss curve: Elbow: Curvature	Loss curve: Elbow: Length	Loss curve: Upper part: Slope	Loss curve: Upper part: Character	Remarks
1	Mershon Telluride	Normal	Sharp	Short	Steep	Nearly straight	Short line at high altitude
2	Smith Worcester	"	Very sharp	Very short	"	Straight	Neutral grounded; probably responsible for high convection loss and high critical loss and high critical corona voltages,
3	"	Above normal	Sharp	Short	"	Nearly straight	
4	"	Large	Sharp	"	Very steep	Straight	
5	Mershon Niagara	Normal	Sharp	Short	Steep	Nearly straight	In this series the relation of loss by convection and loss by part corona is well brought out. With small conductors and, therefore, low voltages, loss by convection is much less than loss by part-corona; with the larger conductors and, therefore, higher voltages, loss by convection equals loss by part-corona, causing $k_{pc} = 1$ and $k_c = k$
6	"	"	Normal	Normal	Normal	Nearly straight	
7	"	"	"	"	"	"	
8	"	"	Sharper than normal	Shorter than normal	Steep	"	
9	"	"	"	"	"	"	
10	"	"	"	"	"	"	
11	"	"	"	"	"	" "	
12	West Cent. Col.	—	Normal	Normal	Steep	Nearly straight	181-mile 100-kilovolt line open; no receiver connections
12	"	—	Sharp	Short	Very low	"	Same line operated with end receiver loaded
13 and 14	Foote Michigan	The only data available in regard to these Michigan high-voltage lines are those reported in the Electrical World, Vol. 50, p. 850, 1907 and Vol. 54, p. 664, 1909 and by D. B. Rushmore, General Elec. Review, XII, p. 86, 1909, for the Grand Rapids 110-kilovolt transmission; Elec. World, Vol. 56, July 14, 1910, p. 86 for tests and data relating to the proposed 135-kilovolt Flint, Mich. transmission. They are rather incomplete for checking corona factors.					

No. 4. This case is of especial interest. The results indicate an unusual electrical state of the atmosphere: Heavy ions, few in number, migrating mostly to the ground urged on by the electric field to earth of the high-voltage line combined with the natural electric field of the earth. The results of this test are the only ones available that show a large convection current, evidently passing to ground, and a small degree of natural ionization about the high-voltage line conductors as shown by the establishment of a remarkably uniform corona requiring a voltage to start it that is almost as high as the standard given by equation 3 and by the concentric cylinders laboratory tests. In fact the results of all three of these Worcester tests wherein the neutral-ground connection was used show the influence of such connection. The aggregate effect of which has been to render higher than normal values of the critical loss-voltage irregularity factor, *k*.

No. 11. The critical loss-voltage of 106 was located by exterpolating the original curve somewhat so as to locate a high-voltage loss equal to double the convection current loss. Doubtless an error of as much as two per cent may have been introduced in this manner.

No. 12. Mr. E. L. West, as assistant general manager for the Central Colorado Power Company, found that the corona loss on this line was much higher with the receiver load off than with it on. He found that with nothing whatever connected to the line a station voltage of 77 kilovolts (effective sine-wave), applied at Shoshone caused part-corona to start on the line conductors over the passes, and that as the voltage was increased the corona loss increased with almost the same rapidity that it would if it had been started simultaneously over the entire 181 miles (291 km.) of line and attained a value, due to corona alone, of 16 kw. per mile (10 kw. per km.) at a station voltage at Shoshone of 105 kilovolts. West and his co-worker Mr. Chas. S. Ruffner made an extensive study of this behavior of the line and found:

1. With the receiver load on, the corona formation was limited to the line-sections through the passes and similar high elevations: that the corona loss started at the same voltage, *viz.*, 77 kilovolts (effective sine-wave), and increased very slowly, attaining a value due to corona along at 105 kilovolts, of about 4 kilovolts per mile (2.5 kilovolts per km.) for the total line, or about one quarter of the loss that occurred with the line open at all points.

2. That the great excess corona loss which occurred when full voltage was applied to the line entirely open, occurred largely on the Denver-Boulder section.

A study of West's data very kindly furnished the author for such purpose, was made having in mind the first principles that must apply in matters of this sort. A summary of the essential line data is given in the accompanying table.

It is seen that the high altitudes occur in the 60-mile (965 km.) section that includes the passes and which constitutes roughly the middle of the three 60-mile sections. The facts and principles presented in this paper show that corona and the electric arc are the same phenomena displayed merely with different proportions as to voltage, current and form of electrodes. The corona formed in the middle section when the line voltage is

above 77 kilovolts acts the role of a *singing arc* to detach energy from the main source and send it oscillating through the *induction-condenser circuit of the Denver end section* at a frequency due to its natural period. The resonance develops great wave distortions in the normal line voltage of the end section. High frequency circulating currents are set up and the highly distorted voltages develop maximum values that exceed the critical corona voltages. Thus as in all resonant effects the up-building of the circulating currents ceases when the losses chiefly due to the corona formed in the Denver section balance the rate at which the corona in the middle section acting as a singing arc can detach energy from the station at Shoshone. Doubtless as soon as the process starts, it goes into turbulence, *i.e.*, the corona wherever formed takes up the role of the singing arc and acts at the same time as a brake on its own behavior.

SHOSHONE-DILLON-DENVER-BOULDER 100-KILOVOLT, 60-CYCLE THREE-PHASE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER CO.

Total miles	Location	Miles in section	6-strand cable B. & S. gauge	Elevation		
				Average feet	Peaks	
					Width miles	Top elevation
0	Shoshone	—	—	6,000	—	—
		52	0	8,000	—	—
52	Hagerman Pass	—	0	10,500	2.5	12,000
		23	0–1	10,000	—	—
75	Fremont Pass	—	1	—	—	11,500
		34	1–0	10,000	—	—
109	Argentine Pass	—	0	12,000	5.5	13,500
		16	0	11,000	—	—
125	Three Peaks	—	0	11,000	16.0	—
		28	0	7,500	—	—
152	Denver	—	0	5,300	—	—
		29	1	6,000	—	—
181	Boulder					7,800*

*Peak near Boulder.

Nos. 13 and 14. Lines of the Commonwealth Power Co., J. B. Foote, electrical engineer, Jackson, Mich. (13) Grand Rapids, 110-kilovolts and (14) Cook-Flint 135-kilovolts (proposed) transmissions. Tests were made by Foote on the Grand Rapids line from which factors were determined for computing the critical loss-voltage (one kw. approximately per mile, at 135 kilovolts) for a three-phase number *o* conductor. It is proposed for this line to operate well into the part-corona range. That this is actually done on the 110-kilovolt Grand Rapids line may be seen by a glance at the photograph of this line taken at night in normal operation, reproduced in Fig. 29, kindly loaned for the publication of this paper by Mr. D. B. Rushmore.

Nos. 15 and 16. These tests were made at Stanford primarily for the purpose of comparing the corona losses indicated on the screen of the electrostatic power-diagram indicator with the visual effects. They were not primarily undertaken to secure results to be placed in the above table. When the table was prepared it seemed as though it might be well to add the results of these tests because they were obtained from thoroughly insulated lines mounted in a large indoor space and in a climate and at a season wherein the atmosphere is known to be at a normal state of ionization in the open.

Conclusions In Regard to the Open Atmosphere as an Insulator.

1. Ionization and the travel of ions under electric stresses are the causes of failure of the open atmosphere as an insulator and they are the cause of corona formation.

2. All ordinary failures of the atmosphere under stress are developed through ionization by collision which can be started under usual high-voltage electric stresses through the presence of some natural or antecedent supply of ions.

3. Variation in the supply of natural ions in open air is the cause of the erratic variation of critical loss-voltages. Such variations have little effect upon the values of the part-corona voltage that has increased the atmosphere loss by the small amount equal to the loss caused by the inevitable ion-convection current.

4. The figure of the electric field about the high voltage conductors determines the facility with which the migrating ions will concentrate the electric stress near the surface of the conductor and thus render the resulting corona irregular at all stages, causing it to be started and to be maintained at correspondingly lower voltages.

5. The turbulent elements introduced by variations in the amount of natural ionization have so small an effect upon the corona forming voltages, and the field irregularity factor above referred to is so nearly constant over a wide range of conditions, that the rational formula as developed should be found dependable to a reasonable extent.

6. The term "*dielectric strength*" as applied to the open atmosphere, from the inherent nature of things, can have no definite meaning.

7. The rupturing strength of the normal atmosphere rests upon two factors only, (1) quantity of ionization produced by the rupturing voltage, (2) the distance between the electrodes. The rupturing gradient varies from 300 kilovolts per in. (120 kilovolts per cm.) at lowest ionization to 3 kilovolts per in. (1.2 kilovolts per cm.) at highest ionization with no indication

that the limits at either end of this range have as yet been found.

Conclusion in Regard to Dry Transformer Oil As an Insulator.

1. The failure of the oil as an insulator is due to ions liberated by the electric stress from the supply of free ions in the metals of the electrodes.

2. The electric stress required to detach ions from metals to the oil is much lower than the corresponding stress for a gas.

3. The further conclusion follows necessarily that a compressed gas must, in regard to *insulating quality alone*, be superior to oil.*

Appendix

[*Reprinted from* SCIENCE, *N. S., Vol. XXXII, No.* 826, *Page* 608, *October* 28, 1910]

The Nature of Electric Discharge†

At a meeting of the Academy of Science of St. Louis, on October 17, the writer presented photographic plates which strongly confirm conclusions reached in former papers.[1] Pin-head terminals rest with their rounded heads upon the film of a photographic plate. Their distance from each other is about 7 cm. One terminal is grounded in the yard outside of the building. The other leads to a variable spark-gap at the negative terminal of an 8-plate influence machine, the positive terminal being grounded on a water-pipe. With very short spark-gaps, the passing of a single spark produces discharge images immediately around the pin-heads. Increasing the spark-length enlarges the images, which are in the nature of brush discharges. The negative glow around the pin-head which communicates with the negative terminal of the machine increases very little in diameter, and the discharge lines in it are radial. The discharge lines around the grounded pin-head for short sparks follow approximately the lines of force. With longer sparks

*In addition to the references already made the author acknowledges the great assistance he has received from Professor Ernest Merritt of Cornell University, Professor Francis E. Nipher of Washington University, and Professor F. J. Rogers of Stanford University; likewise the hearty helpful coöperation of his co-workers, Professors Charters and Hillebrand and of the authorities of Leland Stanford University whose cordial approval of work of this kind made the necessary experimental facilities possible.

[1]*Trans. Acad. of Sc. of St. Louis*, XIX., Nos. 1 and 4.

†See Figs. 11, 12*a*, 12*b*, 13, 14*a*, 14*b* and 14*c* of the present paper.

they are somewhat distorted, as if beaten back by a blast from the opposite or negative terminal. As has been suggested in the papers referred to these discharge lines in the "positive column" are drainage lines, along which Franklin's fluid is being conducted into the positive or grounded terminal. The portions of the air molecules which constitute the stepping stones for the negative corpuscles are urged in a direction opposite to that in which the negative discharge is flowing, thus promoting the lengthening of the drainage lines. Many hundreds of plates have been exposed in an attempt to adjust the spark-gap so that these drainage lines would end just outside of the negative glow without reaching it. In this way the length of these lines may be gradually increased until they approach the dark space around the negative glow. This dark space is a region where convection of atoms which have been supercharged within the negative glow are urged by convection away from the negative terminal. If the drainage lines reach this convection region, they cross it and reach the negative glow. It has thus far been found impossible to have them end within this Faraday dark space. If the spark-gap at the machine is so adjusted that only one or two drainage lines reach the negative glow, these lines will unite end on with the radial discharge lines of the negative glow. At the same time there is a distortion in the lines at and near their union, which reveals the commotion produced by the opposing "electric winds."

If now the spark-gap at the machine be slightly increased, other drainage lines reach the negative glow. They cross its radial discharge lines, and even extend beyond the negative terminal. In a few cases the entire area of the negative glow is traversed by these drainage lines. It is evident that we have here the same conditions that Goldstein found in the vacuum tube. These drainage lines are the canal rays of the vacuum tube.

This explanation of the nature of electric discharge enables us to understand why the positive column in a vacuum tube follows the tube in all of its windings and bends. It is not a convection column, but a drainage column. It is a conduction column. The conditions are different from those in a copper wire, in that the parts of the atoms which constitute the conductor are in gaseous form, and are capable of yielding to the force which urges them in a direction opposite to that in which the negative corpuscles are being urged.

FRANCIS E. NIPHER.

A communication presented at the 255th Meeting of the American Institute of Electrical Engineers, New York, January 13, 1911.

HIGH-VOLTAGE LINE LOSS TESTS MADE ON THE 100-KILOVOLT 60-CYCLE 180-MILE TRANSMISSION LINE OF THE CENTRAL COLORADO POWER COMPANY

[COMMUNICATED TO HARRIS J. RYAN BY E. L. WEST AT THE REQUEST OF THE HIGH-TENSION TRANSMISSION COMMITTEE OF THE A.I.E.E.]

Somewhat over a year ago, Mr. West then assistant general manager and now general manager of the Central Colorado Power Co. made a careful series of high-voltage line loss, wave-distortion and charging-current tests. He gave the writer copies of the results of these tests at the time they were obtained because of the wish on the part of the latter to make a study of the fundamental principles of their highly interesting characteristics. Mr. West has consented to the publication of the data referred to above in the following charts:

The Shoshone station voltage wave form is excellent, being nearly sinusoidal.

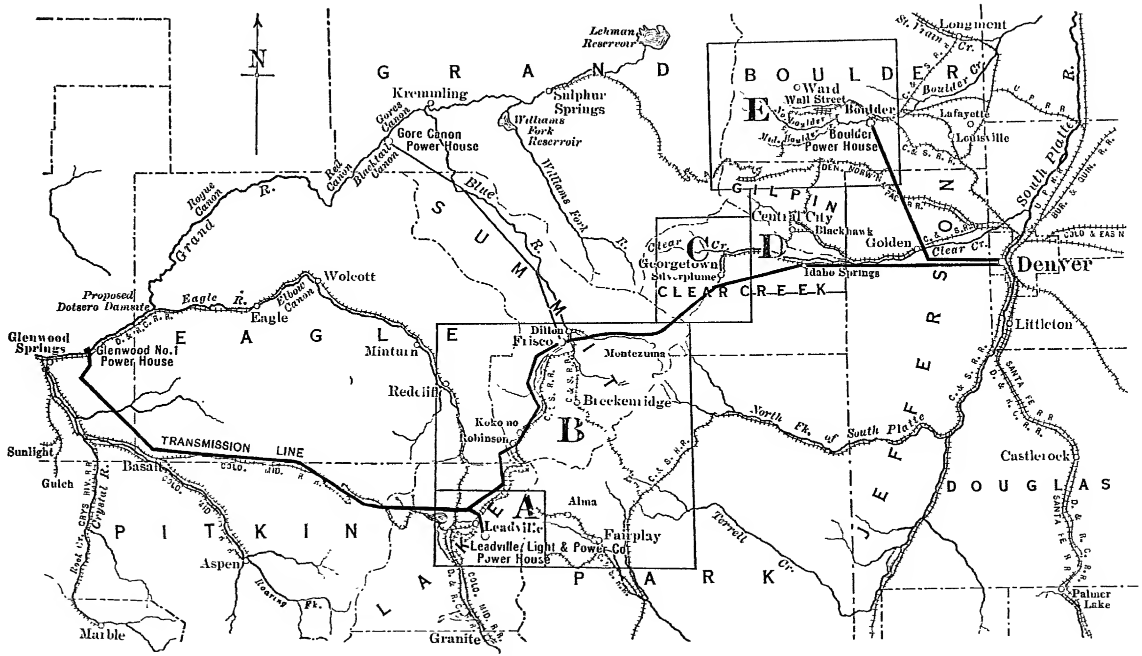
All banks of transformers are delta-connected.

The sizes and corresponding locations of line conductors are given on their charts whence their location may be made on the profile map, Fig. 2. They are six-strand hemp-core copper conductors mounted horizontally, in line, outers 10 ft. $4\frac{1}{2}$ in. (3.15 m.) from the center.

Tower spacings average 750 ft. (228 m.). Suspension insulators disk type, four disks $10\frac{1}{4}$ in. (26 cm.) in diameter connected with solid copper links.

In a letter to the writer dated September 14, 1910, Mr. West says: "I spent a great deal of my time in the generating stations when the line was put into operation and I took the ob-

MAIN TRANSMISSION LINES OF CENTRAL COLORADO POWER CO.



Lines extend from Shoshone Power House near Glenwood Springs to Denver, 153 miles
The main transmission lines of the Boulder Project, 29 miles long, are also shown
Fig. 1

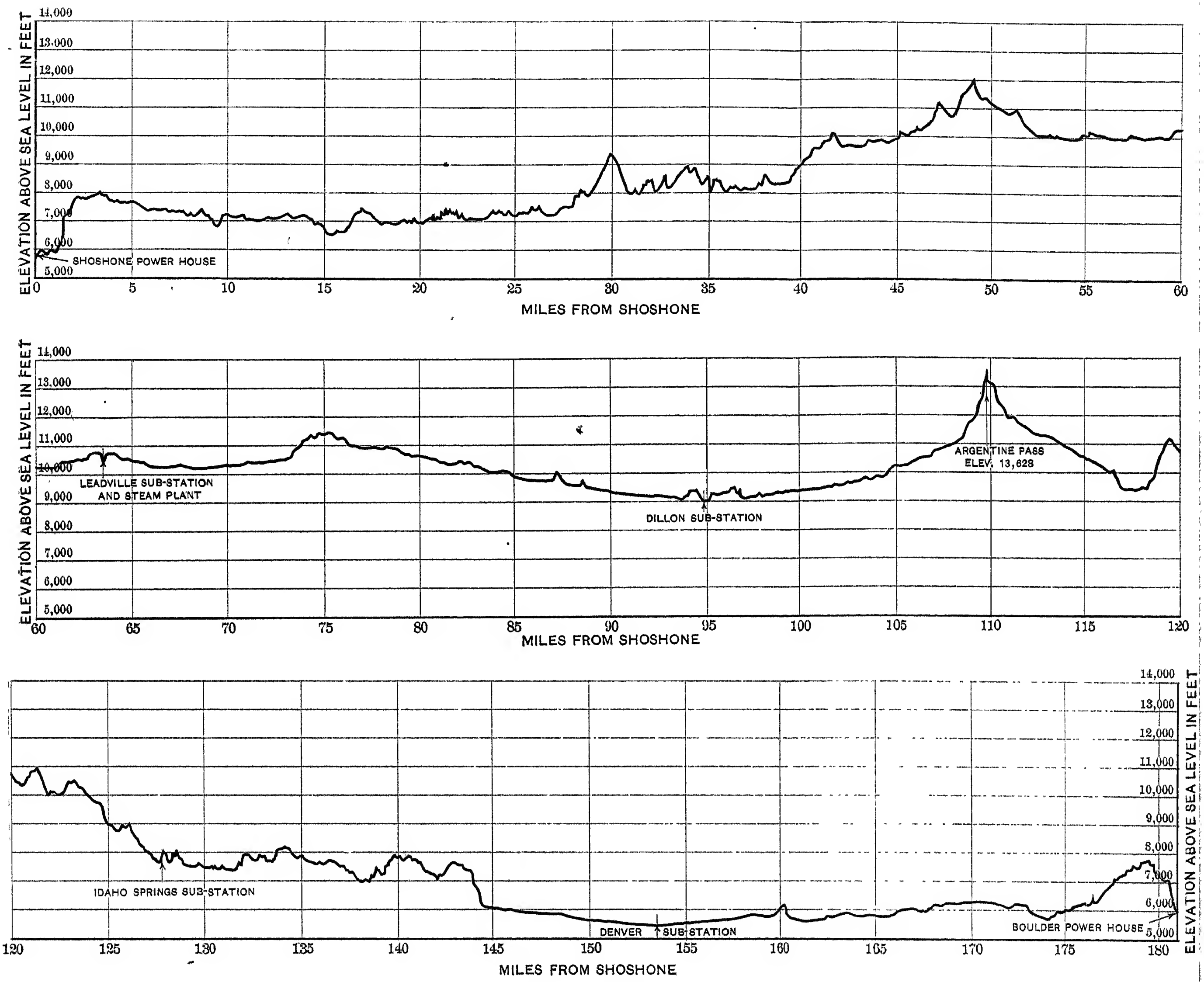


FIG. 2.—Profile of transmission line. Shoshone to Denver-Denver to Boulder

[West p. 78]

servations myself and used every means possible to secure accuracy. When the rheostat load tests were made I stationed the operators, who had previously been trained to obtain accurate observations, at the Shoshone or generating end of the line, while I conducted the test from the Boulder or load end of the line. In order to get simultaneous readings I signaled the telegraph operator at Shoshone over our telegraph line by repeating the letter R at intervals of about five seconds. The observers at Shoshone could hear the telegraph instrument so in this manner we obtained simultaneous readings at both ends of the line. In addition to this we had curve-drawing instruments for voltage and kilowatts at both ends of the line and all instruments were calibrated carefully before and after the test. After the observations were taken I compared the curve-drawing instrument charts and in this way was able to eliminate any errors of observation, so that I believe the data obtained are nearly as reliable as a test conducted in a laboratory where all instruments would be located at one point."

Again in a letter dated August 11, 1910, Mr. West writes:

"As I understand it, the specific question you would like answered is whether the difference in results shown by tests No. 7 made on July 23, and tests No. 10 made on November 14 can be explained by difference in atmospheric conditions. Both Mr. Charles S. Ruffner, our operating superintendent, and I do not think this difference is due to weather conditions, but believe that it is due to different connections of transformers to the line. You will note in test No. 7 that transformers were connected at Leadville, Dillon and Denver, and there were 30 miles (48 km.) on the end of the line from Denver to Boulder which had nothing connected to them; *i.e.*, during this test there were no transformers connected at Boulder where the line voltage was highest, whereas, during tests No. 10, transformers were connected at Denver and Boulder only, with no other intermediate connections from Denver to the generating station.

"From here on I will let Mr. Ruffner dictate:

"We believe that the differences in load shown on the same length of line may obtain under different conditions of transformer connections, being particularly affected by the location of such transformers.

"On this particular system the connection of transformers (while adding small losses in the transformers themselves) decreases the total loss, by reason of local non-uniform reduction

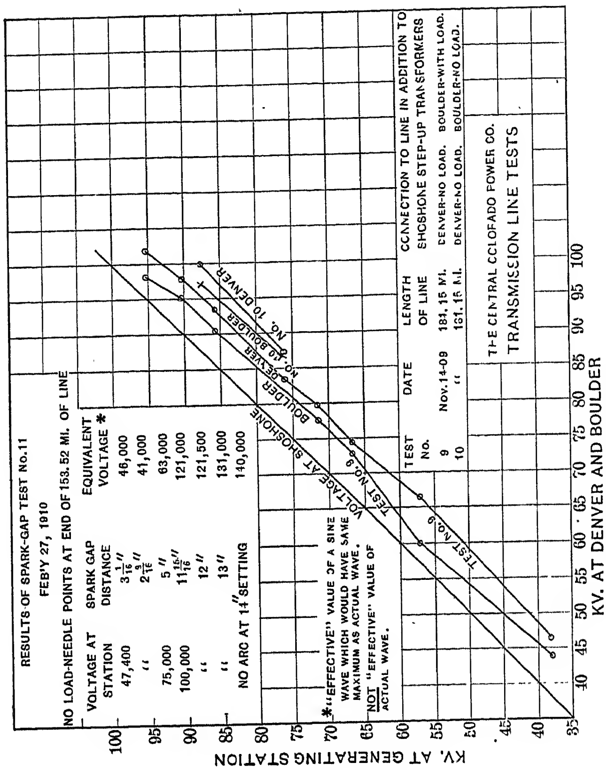

RESULTS OF SPARK-GAP TEST No.11
FEB'Y 27, 1910
NO LOAD-NEEDLE POINTS AT END OF 153.52 MI. OF LINE
VOLTAGE AT STATION | SPARK GAP DISTANCE | EQUIVALENT VOLTAGE *
47,400 | 3 1/16" | 46,000
" | 2 9/16" | 41,000
75,000 | 5" | 63,000
100,000 | 11 15/16" | 121,000
" | 12" | 121,500
" | 13" | 131,000
NO ARC AT 14" SETTING | | 140,000
*"EFFECTIVE" VALUE OF A SINE WAVE WHICH WOULD HAVE SAME MAXIMUM AS ACTUAL WAVE. NOT "EFFECTIVE" VALUE OF ACTUAL WAVE.
NO. 10 DENVER
NO. 10 BOULDER
DENVER
BOULDER
VOLTAGE AT SHOSHONE
TEST NO. 9
TEST NO. 9
TEST No. | DATE | LENGTH OF LINE | CONNECTION TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
9 | Nov. 14-09 | 184.15 MI. | DENVER-NO LOAD. BOULDER-WITH LOAD.
10 | " | 161.15 MI. | DENVER-NO LOAD. BOULDER-NO LOAD.
THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
KV. AT GENERATING STATION
KV. AT DENVER AND BOULDER

FIG. 4

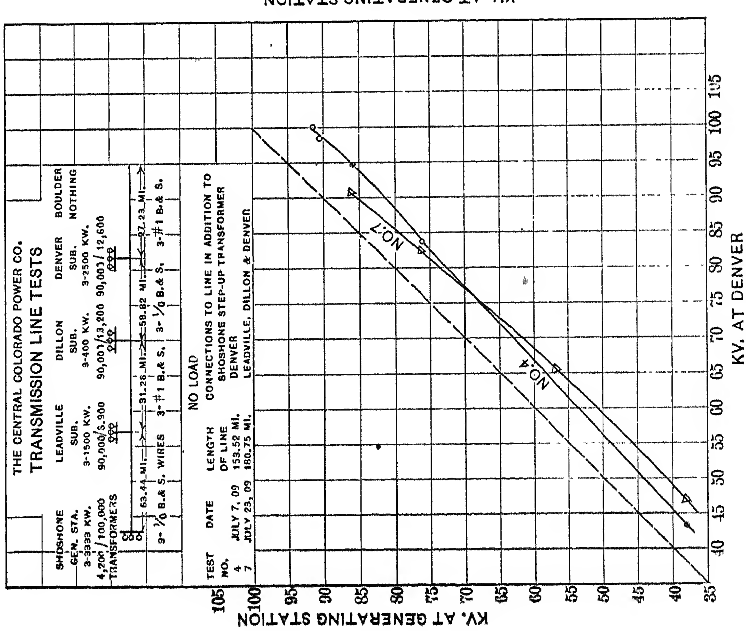

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-3333 KW. 4,200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/5,900
DILLON SUB. 3-400 KW. 90,001/13,200
DENVER SUB. 3-2500 KW. 90,001/12,600
BOULDER NOTHING
63.44 MI.
31.26 MI.
58.82 MI.
27.23 MI.
3-1/0 B.& S. WIRES
3-#1 B.& S.
3-1/0 B.& S.
3-#1 B.& S.
NO LOAD
TEST NO. | DATE | LENGTH OF LINE | CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMER
4 | JULY 7, 09 | 153.52 MI. | DENVER
7 | JULY 23, 09 | 180.75 MI. | LEADVILLE, DILLON & DENVER
NO. 7
NO. 4
KV. AT GENERATING STATION
KV. AT DENVER

FIG. 3

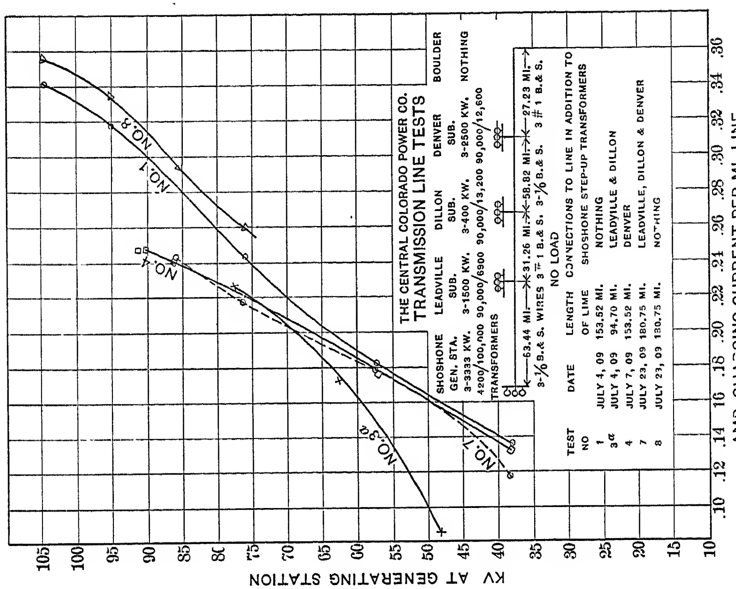

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
NO LOAD
KV AT GENERATING STATION
AMP. CHARGING CURRENT PER MI. LINE

FIG. 6

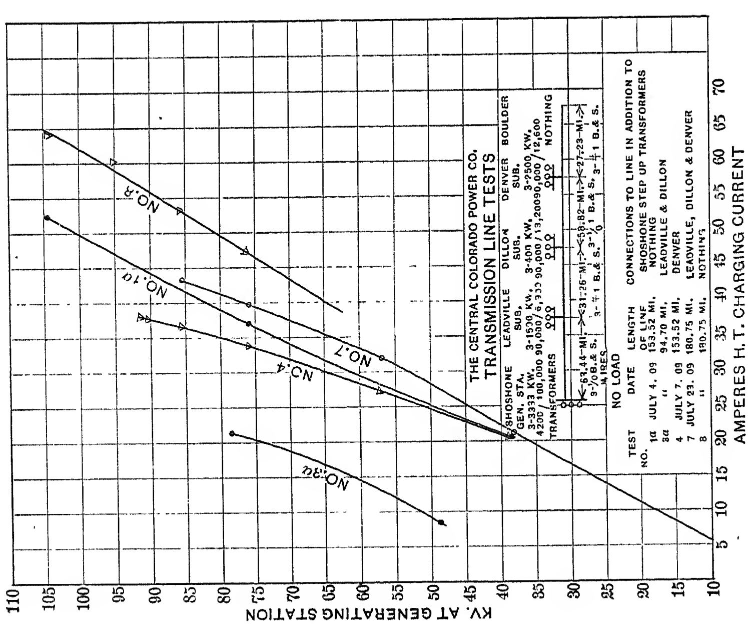

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
NO LOAD
KV. AT GENERATING STATION
AMPERES H. T. CHARGING CURRENT

FIG. 5

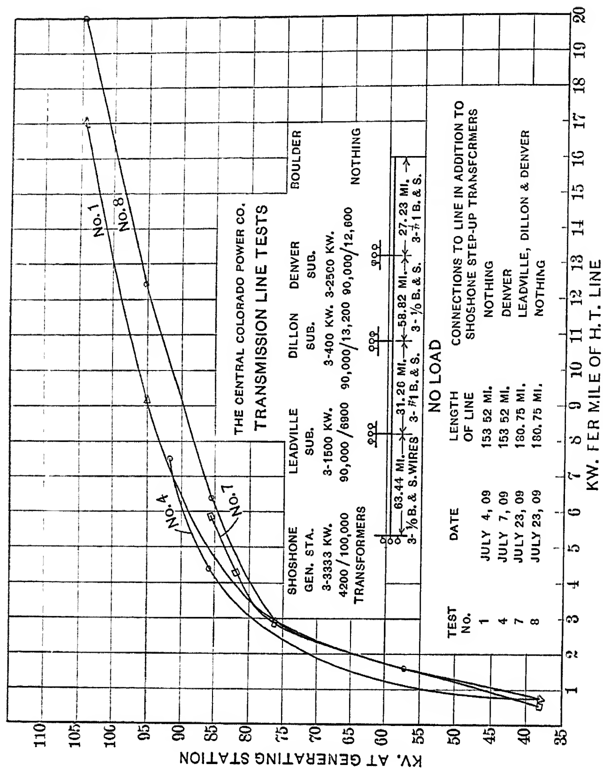

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-3333 KW. 4200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/6900
DILLON SUB. 3-400 KW. 90,000/13,200
DENVER SUB. 3-2500 KW. 90,000/12,600
BOULDER
NOTHING
63.44 MI. 3-1/0 B. & S. WIRES
31.26 MI. 3-#1 B. & S.
58.82 MI. 3-1/0 B. & S.
27.23 MI. 3-#1 B. & S.
NO LOAD
TEST No.
DATE
LENGTH OF LINE
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
1
JULY 4, 09
153 52 MI.
NOTHING
4
JULY 7, 09
153 52 MI.
DENVER
7
JULY 23, 09
180. 75 MI.
LEADVILLE, DILLON & DENVER
8
JULY 23, 09
180. 75 MI.
NOTHING
No. 1
No. 8
No. 4
No. 7
KV. AT GENERATING STATION
KW. PER MILE OF H.T. LINE

FIG. 8

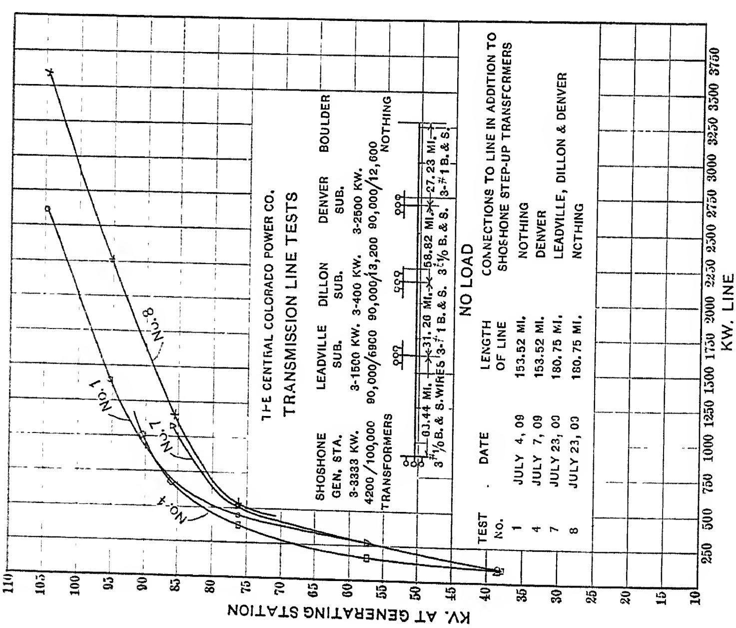

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA. 3-3333 KW. 4200/100,000 TRANSFORMERS
LEADVILLE SUB. 3-1500 KW. 90,000/6900
DILLON SUB. 3-400 KW. 90,000/13,200
DENVER SUB. 3-2500 KW. 90,000/12,600
BOULDER
NOTHING
63.44 MI. 3-#1/0 B. & S. WIRES
31.26 MI. 3-#1 B. & S.
58.82 MI. 3-1/0 B. & S.
27.23 MI. 3-#1 B. & S.
NO LOAD
TEST No.
DATE
LENGTH OF LINE
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
1
JULY 4, 09
153.52 MI.
NOTHING
4
JULY 7, 09
153.52 MI.
DENVER
7
JULY 23, 09
180.75 MI.
LEADVILLE, DILLON & DENVER
8
JULY 23, 09
180.75 MI.
NOTHING
No. 1
No. 8
No. 4
No. 7
KV. AT GENERATING STATION
KW. LINE

FIG. 7

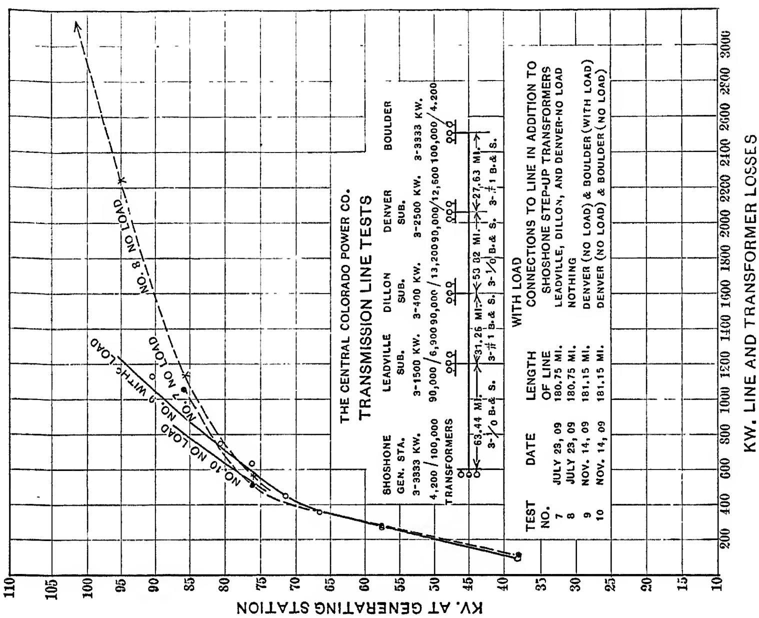

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
SHOSHONE GEN. STA.
LEADVILLE SUB.
DILLON SUB.
DENVER SUB.
BOULDER
TEST NO.
DATE
LENGTH OF LINE
WITH LOAD
CONNECTIONS TO LINE IN ADDITION TO SHOSHONE STEP-UP TRANSFORMERS
KV. AT GENERATING STATION
KW. LINE AND TRANSFORMER LOSSES

FIG. 10

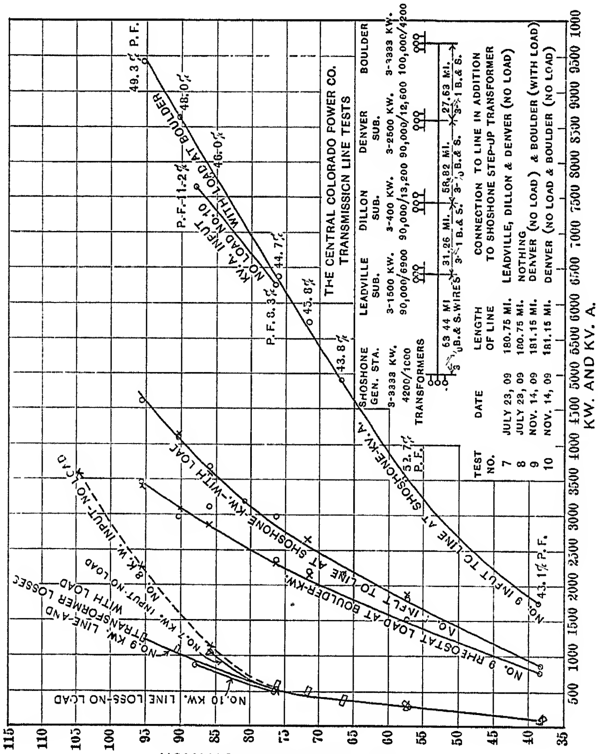

THE CENTRAL COLORADO POWER CO.
TRANSMISSION LINE TESTS
KV. AT GENERATING STATION
KW. AND KV. A.

FIG. 9

in voltage and modification of wave form. In the case of test No. 7 the increased losses seem to be best explained by considering that the line from Denver to Boulder was open-circuited, and that for the same voltages measured at Denver in the two cases, the corresponding voltages at the Boulder end of the line were greatly different; and that in the test No. 7, without transformers at Boulder, the potential there was so much above the

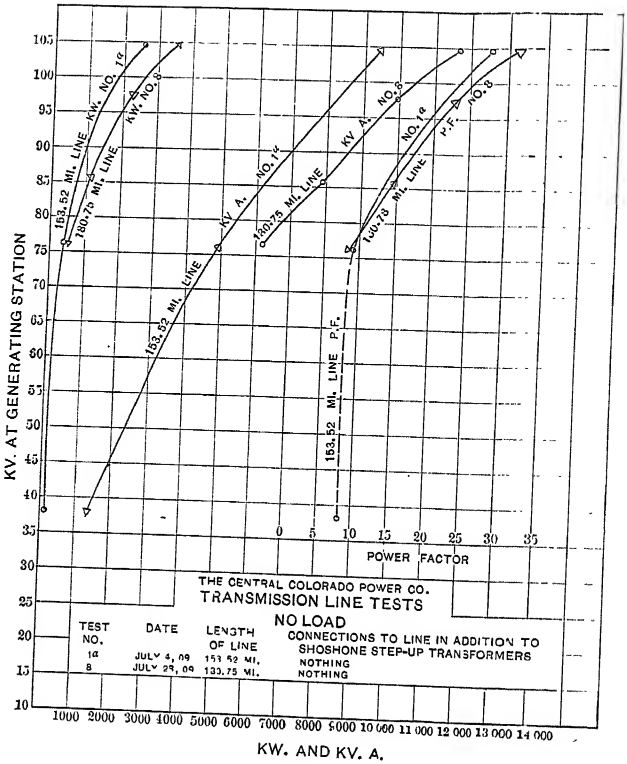


FIG. 11

critical voltage that the losses on that end of the line were very high.

"In the case of an open-circuited line on which the rise in potential is uniform throughout its length, the corona losses would, of course, not be uniform but would be several times greater at the open-circuited end. In fact, in some cases we believe that under open-circuited conditions the voltage is below the critical voltage at the power house end and is very

much above the critical voltage at the open circuited end, thereby producing the greater part of the loss at the open end of the line.

"We believe that another factor causing the difference between tests No. 7 and No. 10 is the location at which transformers were connected, because this effect is shown by the differences between tests No. 1 and No. 4. The effect of connecting intermediate transformers is to reduce the voltage below the critical value at several intervals along the line thereby preventing the average voltage over the length of the line raising as high as it undoubtedly would in case transformers were connected at but one point."

Discussion on "Open Atmosphere and Dry Transformer Oil as High-Voltage Insulators", New York, January 13, 1911.

M. I. Pupin: In this paper we have a treatise on the electron theory in its application to the explanation of phenomena which take place on high potential transmission wires.

I am glad that makes it unnecessary for me to discourse here on the electron theory. I will only say that the engineer who proposes to study the phenomena which accompany high potential transmission, cannot get along at all without this magnificent theory. It is a theory which makes an epoch in the development of electrical science. Professor Ryan has done well to grapple this theory and see whether he could coördinate the very numerous experimental facts which engineers have observed from time to time in connection with high potential transmissions, particularly in connection with this most bothersome phenomenon, corona discharge from wires.

When I was studying in the University of Berlin, there was a doctor there named Knorr, who was investigating the subject of the electrification of perfect gases, and he came to the conclusion that perfect gases cannot be electrified. This means that perfect gases cannot be decomposed by any electrical stress. By perfect gases I mean oxygen or hydrogen or any other ideal gas which is absolutely pure, or as pure as human hands can make it. This fact was known prior to our knowledge of the electron theory, and is admitted to-day.

Another thing which was found prior to the electron theory, was, that if we take two metallic electrodes, and put them in a vessel, and then make as perfect a vacuum as we can with our modern methods of extremely low temperatures, then no electrical tension, no matter how high, between these electrodes, can produce a discharge between them. That means that unless there is some matter between metallic electrodes, electricity cannot be passed from one electrode to another.

Now, if we cannot get any electricity out of a perfect gas by any tension whatsoever, and we cannot get any electricity from metal electrodes without any matter between them, or with a perfect gas between the electrodes, then it seems to be demonstrated that the perfect gas between two metallic electrodes cannot be a vehicle of electricity between these two electrodes, no matter how high the potential. I think the logic of that will be admitted.

If a perfect gas between two clean metallic electrodes cannot convey electricity from one electrode to the other, under the influence of any electrical stress under our disposal, what is going to do it.

Professor Ryan says, and correctly, the ions of electricity that are there. You must have electrons there, free electrons or free ions. He calls that "dirt" in one part of his paper, but it is

not to be understood as ordinary dirt. It is the presence or a mixture of some foreign substance which does not belong there, for if we have clean electrodes and a pure gas, anything else that is present, is "dirt" in that sense.

. If the dirt were not there, we could not pass an electrical current by any stress because we do not produce the electrical current between the conductors. That current is not produced by the simple breaking down of something under electrical stress. The electrical field takes a free electron and accelerates it, and when a free path in which an electron moves is long enough for the force, the velocity attained by the electron may be sufficient that when it collides with some atom in this space between them, we get more electrons. That is the source of supply—ionization by collision.

The smallest particles, the electrons, produce the ionization by collision because on account of their smallness they will attain the highest velocity under the same accelerating force, the mass being so extremely small.

The ionization power of the moving electrical charge, depends not on the velocity of the particle multiplied by its mass; it depends on the product of its velocity into its electrical mass. If the electrical mass is small, and the gravitational mass is large, the ionization will be small, whereas if the gravitational mass is large, and the electrical mass is small, then the electro-kinetic momentum obtained will be very large.

There is one thing I will add to what Professor Ryan has said, and which seems to me to be quite important. That is, the potential is not equally divided over the distance between two electrodes. When the difference of potential between two electrodes of very large length, is 100,000 volts, and the distance between these two electrodes is two inches, it would be wrong to say that for every point between these two electrodes, the force per unit length was 100,000 volts. It is far from true, because it may have been ten times as much close to the electrodes and very much less in the middle of the distance between them. So that in all experimental operations on electrical discharges, we have to be careful when we specify what the potential gradient is at any given point. We must, in order to specify it correctly, or we should know the amount of free electrons that the space between the two electrodes contains. The amount of these free electrons will modify the potential gradient, making it considerably larger nearer the electrodes, and considerably smaller at points distant from the electrodes.

If the two electrodes, however, are very close together—say 1/100th of an inch from each other, then we would get results which are very near correct. All experiments in which the potential gradient was found to be 76 kilovolts were made with the electrodes very close together.

Professor Ryan attaches a great deal of importance to the tendency of the discharge through the gas to form a core.

At the negative electrode there is a uniform discharge, and at the positive electrode when a certain current density is reached, there are then filaments or streamers like a brush discharge. When the potential is raised and the luminosity is increased on the brush we get a beautiful corona, and then a spark, or the formation of an arc. When that occurs, the electricity runs through a single channel and no flow occurs anywhere else.

According to Professor Ryan, and I agree with him, that is caused by the so-called dynamic force between the elements of these currents. In air, under ordinary pressures, the electrodynamic force or attraction is greater than the repulsion.

This paper is a treatise, and nothing else, on the subject of applying the electron theory for the purpose of co-ordinating all our experimentally observed phenomena of electrical discharges from high potential transmission wires. When we consider the kind of a treatise this is, it can easily be seen that the paper is not one that lends itself very much to discussion.

G. Faccioli: Professor Ryan has referred to some experiments which Mr. Moody and myself performed two years ago. I will answer the questions which Professor Ryan has asked in connection with these experiments.

We started our tests by using concentric cylinders, but we found that the edge of the outside cylinder introduced a considerable error in the results. We then adopted the other form of condenser constituted by a small cylinder parallel to a plate.

The results were the same whether both the electrodes were ungrounded or whether one electrode was grounded. Furthermore, if the size of the plate was reduced, the full corona voltage of the rod was not affected. If, however, the plate was entirely removed, then of course, the corona voltage rose to very high values.

I think that the results were not disturbed by the fact that the air had some absolute potential, but our tests, which extended over a period of several months, proved that the bodies in the immediate neighborhood of the electrodes and especially of the small cylinder (where the electrostatic field is most intense) are responsible for the discrepancies between the values obtained by test and the values given by formula.

The suspension and excitation of the rod are the most important elements of disturbance. If the rod is energized from both ends, then corona will start in the middle and spread gradually toward the ends. If, however, the rod is energized from one end only, then corona will start at the free end, and spread toward the excited end, the full corona voltages being different in the two cases. Our tests, were undertaken to study the behavior of apparatus of limited dimensions, and therefore the influence of the rod suspension, etc., was carefully studied and no attempt was made to eliminate it.

The paper by Mr. Moody and myself, shows the behavior of the electrostatic field when a piece of insulating tape is wrapped

around the surface of the small cylinder. In this case a brush starts at the edges of the solid insulation at a voltage considerably lower than the voltage necessary to produce full corona on the rod. This phenomenon shows that to the two classes of "dirt" which Professor Ryan has pointed out, a third class should be added, namely, the "dirt" produced by insulating materials on the surface of the conductors. This class of "dirt" is very important, as to this class belong, for instance, the line insulators.

I have seen part-corona formed on high-tension lines at comparatively low voltages in spots where the hemp center of the conductor was projecting between the copper strands.

This phenomenon given by solid insulation wrapped on the surface of the conductor when the dielectric is air, does not occur when oil is used as dielectric. For instance, in one of the examples shown by Professor Ryan, we have a rod $\frac{1}{8}$ in. (3.17 mm.) in diameter, 15 in. (38 cm.) long and $6\frac{1}{2}$ in. (16.5 cm.) away from a plate. When the system is in air, then corona starts on the rod, at 45,000 volts. If, however, a piece of insulating tape (specific capacity, 4.5) is tied on the rod, a brush will start at the edge of the tape at 37,000 volts.

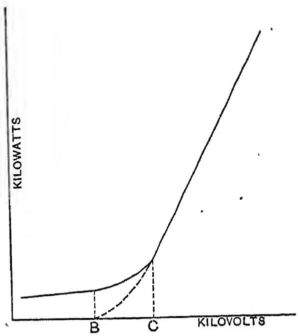


FIG. 1

Now, if the system is immersed in oil, part-corona starts at 100,000 volts, whether the rod has solid insulation on its surface or not. Even if we use insulating materials of specific capacity far above the specific capacity of oil, this phenomenon, which is so prominent in air, is absent under oil.

This confirms Professor Ryan's theory that the formation of corona in air and oil is due to different causes, in the former case being produced mainly by "collision"; in the latter case being produced by the fact that the electrostatic field helps the molecules of oil to extract the electrons from the surface of the conductor against the attraction of the metallic molecules.

As to the tests on the line of the Central Colorado Power Company, I am presenting a paper to the American Institute of Electrical Engineers on this subject, and the paper is published in the January, 1911 PROCEEDINGS. I will, however, discuss rapidly two or three points now. Professor Ryan distinguishes three different stages of corona; First, sub-corona, when losses are present, but no luminous phenomena occur. Second, part-corona when the conductor glows in spots. Third, full corona, when the surface of the conductor is entirely surrounded by corona.

The curve which gives the kilowatts in function of the kilovolts, has three distinct parts: A lower part, an elbow and an upper part. (See Fig. 1.)

I do not think that sub-corona corresponds to the lower part, part-corona to the elbow and full corona to the upper part. In fact, in the case of the Central Colorado Power Company's line, the losses above the critical voltage are represented by a quadratic equation of the form $K\,(E—V)^2$, where K is a constant, E the applied voltage, and V a constant critical voltage.

In this case V is 80 kilovolts, (point B in the figure) and the voltage C at which the upper part of the loss-curve begins, is 107.5 kilovolts.

This means that from 80 to 107 5 kilovolts, the elbow of the curve is composed of two parts; one part given by full-corona losses and the other part given by part-corona losses.

As to the critical voltage of the Central Colorado Power Company's lines, Professor Ryan has deduced the value of 77 kilovolts from curves which give the losses of 150 or 180 miles of lines. In this case the abscissae of the curve are the kilovolts at the generator end of the line. But, the voltage of the far end of the line is considerably higher than at the generator end. It seems, therefore, that the value of 77 kilovolts is rather low. From tests which I have taken on short lengths of line of this system, this critical voltage appears to be somewhat higher than 80 kilovolts.

The rise of voltage at the far end of the line, is attributed by Professor Ryan mainly to resonance. Oscillograms of electromotive force and charging current taken at the power house, give sine waves. A step-down transformer was connected at the far end of the line at Denver (line unloaded) and the wave of the electromotive force across the secondary of this transformer was also a sine wave. This shows that resonance is not a prominent factor and the rise of potential at the far end of the line can be simply explained by the flow of charging current through the inductance of the line.

The curve of losses is so steep in the upper part that the high voltage at the far end explains the high losses which are concentrated at this far end.

In connection with the rise of potential at the open end of the line, I wish to call attention to the fact that in Fig. 4 of Mr. West's communication the voltages corresponding to the spark-gap distances are taken from the standard curve of the American Institute, which is correct at sea-level.

The tests, however, were taken at Denver, which is a mile (1.6 km.) high, and therefore, the actual voltages represented by the sparking distances are lower.

I have taken some tests with spark-gap at Leadville, Colorado, which is 10,500 ft. (3200 m.) high, and by interpolating between the standard curve and the curve obtained at Leadville, I obtain for a 14-in. (35.56 cm.) gap a striking voltage of 115,000 volts instead of 131,000.

Professor Ryan's paper covers such a vast field, from the theory of composition of matter to the most practical problems

of line design, that I agree with Dr. Pupin that the best way of discussing the paper is to contribute experimental data. It is immaterial after all whether the electron theory represents absolute truth or not. I welcome this theory which allows the engineer to get a physical picture of the phenomena involved in the disruption of dielectrics.

Mr. Moody and myself have planned to continue our experiments, and have at our disposal 750,000 volts which will allow us to magnify the phenomena, and with Professor Ryan's coöperation we hope to prove the beautiful theories which have been disclosed in this classical paper to-night.

C. P. Steinmetz: I consider Professor Ryan's paper as a continuation of his classic of 1904. In his previous paper Professor Ryan reviewed and analyzed our knowledge of the behavior of air at high voltages, and produced a theoretical formalism representing these phenomena, which has been the basis of all investigations made since that time on the atmosphere at high voltages. His present paper is a continuation of this; and herein I find its great value; in the correlation of the vast amount of experience which has been collected since his 1904 paper, and in the general results derived therefrom.

The present paper is written in the language of the ionization theory, but this I consider merely as an incident and not an advantage, but from my point of view, rather as a disadvantage. In spite of frequent serious endeavors, I have not been converted to the ionization theory, and believe that the theory is not such as to appeal to the engineer, as engineers have to deal with the relations of energy and power, and any speculation on the ultimate condition of matter cannot appeal to us as strongly as to the speculative philosopher or the physicist. Furthermore, as engineers, we must be more careful in the selection of our tools. To the physicist a brilliant theory may appeal. The engineer, however, is confronted with the serious disadvantage in using hypotheses, that usually after a few months all his calculations are checked by the experience with the completed structure, whether transmission line, engine or apparatus, and if the theory was wrong, disaster overtakes the work and the reputation of the engineer. Therefore he must be more careful than the physicist, in whose calculation an error usually is not so serious, as the paper containing it may be withdrawn and corrected, and no harm is done. It is just in this feature that I found the ionization theory to fail. I have never been able to predetermine anything by this theory that I could not predetermine with far more confidence and correctness without this theory. But I have seen predeterminations which were not verified afterwards; although I must say that in every instance afterwards it was found that the ionization theory could be modified to fit the experience. But that is not satisfactory to the engineer, and therefore I do not have much use for the ionization theory.

Coming now to the valuable paper of Professor Ryan, it is not possible to discuss it in its correlation and analysis of facts but it must be studied and digested, and I can only refer to a very few points.

The first of these is the final demolition of the theory of the layer of condensed air which I once was guilty of proposing, many years ago. That was a physical speculation, however. Professor Ryan now brings conclusive evidence corroborating the statement which I made in a discussion a few months ago on the nature of the appearance of the corona: Visual corona appears, not when the voltage gradient has exceeded the critical value at some point in space, but when the range of space where the critical voltage is exceeded, has reached a finite value; that is, to form a corona, it is not merely necessary to have a sufficient voltage gradient, but a sufficient distance covered by this voltage gradient. That is, not only voltage gradient, but voltage or energy is required. That explains the anomaly that the gradient at the conductor when the current begins to be visible, varies with the diameter. It is not the gradient at the conductor, which is determining, but the gradient over a finite distance; and this finite distance is a function of the diameter, which has not been evaluated as yet.

The second interesting feature is the discussion of the coring effect of the current, as explained by Professor Ryan by the magneto-mechanical force. Another explanation I suggested some time ago in the discussion of a paper here, namely, that this coring up is the result of the electrical nature of the conductor —of the air. When you have a uniform conductor exposed to a uniform potential difference, the current density in this conductor may be uniform; but not necessarily so. Under certain conditions in a uniform conductor at uniform potential differences, uniform current density is unstable; and stable condition is concentration of the current into one or a few narrow channels. This condition occurs when the resistivity of the conductor decreases with increasing current density, at a rate greater than the increase of current.

There are many conductors of this character, including solid conductors which can easily be studied. For instance ordinary anthracite coal: Place a lump of anthracite between parallel plates and increase the voltage, and you will find, no matter how uniform you try to get the lump of anthracite, the current density is not uniform, but finally concentrates in a luminous streak. The condition where uniform current density is unstable may be expressed by the equation:

$$-\frac{d\,r}{r} > \frac{d\,i}{i}$$

where r is the resistivity of the conductor and i the current density. In this case the current will core. All gas and vapors,

as conductors fulfill this condition. We cannot get in them a uniform current density at uniform potential difference.

The next important point of the paper is the statement that air does not have a definite break-down strength, but that it varies with the conductivity of the air. It appears to me from the data of the paper, that no matter what the natural conductivity of the air is—how many or few ions it contains—there should be a definite break-down strength, or a definite potential gradient where corona begins; but with the limitation that there must not only be a sufficiently high potential gradient, but sufficient distance over which this exists to have the voltage to produce conductivity, or distance to produce sufficient ionization by collision. To use the language of the ionic theory: if we have a voltage gradient sufficiently high to bring the velocity of the electron to ionization by collision, then it is immaterial how many or how few ions you have; it is only a question of the distance. The only condition is to have a few ions in the air, have some trace of conductivity and at some definite potential gradient you must get a break-down. But, the time may vary. That is, I can see that the time element of disruptive strength may be a function of the number of free ions, or the conductivity of the air, but I cannot see how the voltage gradient can be a function.

The last point is this mysterious upper limit of final break-down—the 1,000 kilovolts per centimeter, where, irrespective of the absence of ions, a disruptive discharge takes place. What is the meaning of this? It is explained that free ions are produced from the terminals.

We have two forms of conduction of vapors and gases; one is the conduction of the Geissler tube and the electrostatic spark. Professor Ryan shows how these two phenomena, the disruptive spark and the Geissler tube discharge, are identically the same, differing only according to the gas pressure. That is entirely in agreement with the conception I always had. In this kind of conduction, the current is carried by the material which fills the space between the electrodes. That is, the gas ionizes and so becomes a conductor.

There is, however, a second form of conduction, namely, arc conduction, in which the conductor is a vapor stream of electrode material, connecting the two electrodes. There the material which fills the space does not carry the current, but is immaterial and may be absent.

So, you see the second critical voltage of 1,000 kilovolts per centimeter (using the upper limit) represents that electrostatic stress where spontaneous arc conduction begins; that is, conduction by the material of the electrodes, as conducting vapor stream. Whether electrons are expelled from the terminals or the vapor stream is produced by the electrostatic stress, the physicist may speculate; the engineer sees through the spectroscope that electrode vapor passes between the terminals

as conductor of the current, and whether the electrode vapor itself is the conductor, or the ions which permeate it, is of secondary importance. This second critical value thus is the starting point of spontaneous arc conduction. If there is no material in space, that is, an absolute vacuum, at this potential gradient conduction occurs by the conductor issuing from the terminals, so that these 1,000 kilovolts per centimeter would be the disruptive strength of empty space or vacuum. There may be some experimental study for determining the disruptive strength of vacuum.

William Stanley: The corona produced by ionization, the study of which we might well take many evenings to enjoy, is a subject of vast importance. I shall not attempt to add to what the other speakers have said more than to perhaps point out that if the ionization theory is useful and applicable to gases, it should be (mechanically) applicable also to solids. The behavior of the ions within a conductor must bear some simple relation to their behavior outside of conductors; and if Professor Ryan is correct in his assumption that at a voltage of 2300 kilovolts, you can extract pieces of electricity from matter and shoot them off, it is a grave question whether or not you have not then changed the nature of the matter. There is no experimental evidence on this point, nor can I add any; but I have my doubts about the 2300-kilovolt effect. I doubt if it is possible to shoot out of solid material, free electricity without letting some of the matter go with it. I think within the next year we may expect from the engineer, mathematician and the physicist so much more light on the entire subject that the differences of opinion, as to correctness of the theory expressed to-night, will pass away.

There are three different methods of losing energy into air, by convection, by corona and by voltages below corona. I take it that the physicist's theory says that energy is lost by convection when the molecules of the air are charged, repelled and dissipated at slow velocities.

The electric current is a phenomenon due to the movement of negative corpuscles. If a negative corpuscle is sent through gas fast enough, by any means, the phenomena which look like corona will appear. The force which drives a corpuscle at this high speed (electrical speed) is the electrostatic force. The fact that corona is produced by corpuscles shot from a conductor does not matter. If the material discharged consisted of pieces of copper, sent out with the same speed (as corpuscles are sent) we would get the same phenomenon of light (corona).

I have not had time to sufficiently study the paper to permit me to confirm or contradict it, but it is a delightful one and I hope you will have many more of this kind from the same author.

J. B. Whitehead: If I have understood this paper correctly the author considers that corona formation is due to three causes:

1. Spark discharge between the conductor and the neighboring air rendered conducting by diffusion of ions from the opposite conductor.

2. The impact of positive ions on the negative conductor resulting in the giving off of more ions into the air.

3. Ionization by collision between molecules of the air and ions arising as in (2) or from other sources.

I am unable to determine whether the author considers that any one of these causes is sufficient, or that they are coincident, or all parts of one sequence. The experiment of concentric cylinders with short radial separation cited by the author in proof of cause 1 is not conclusive, for under the conditions of the experiment corona and spark voltages are identical and no difference is to be expected; corona cannot be formed under the conditions given. It may be shown that the electric intensities of spark discharge are of a higher order of magnitude than those at which corona start.

Professor Ryan does not give conclusive evidence that impact of positive ions on an electrode may liberate other ions. The cathode ray tube of extremely low pressure may not be relied upon for explanations of phenomena at atmospheric pressure as Professor Ryan, when discussing other matters, has pointed out. A cause for corona of this nature would lead us to expect a difference in corona voltages for different materials of the electrodes, which, however, is contrary to experience. Further, it has been shown in several ways that the electric intensity required to liberate ions from the body of a metallic electrode is of a much higher order of magnitude than that at which air at atmospheric pressures will be ruptured either in the form of corona or spark.

Those who have read my paper, " The Electric Strength of Air " (PROCEEDINGS A. I. E. E., July 1910, p. 1059) will recall that I have suggested secondary ionization, or ionization by collision, as a sufficient cause for corona formation. It is not however necessary to invoke the conductor as a source of the first ions. There are always a sufficient number of free ions in the atmosphere whether indoors or out, inside or outside of tubes, to start ionization by collision. The number of ions under these different circumstances may be quite different at different times, but the vital factor in starting ionization by collision is the electric intensity which must be sufficiently high to accelerate the charged ion to a velocity necessary to ionize the molecule when it collides with it. A greater or less number of the free ions whether due to radioactive emanation, water falls, or other cause does not affect the voltage or intensity at which corona starts.

The author's experiment with two No. 12 wires and one No. 30 wire in between them, the latter excited from an induction machine, does not appear to me to prove the influence of the presence of ions in lowering corona voltage. With the No. 30

wire at a negative potential, since the two No. 12 wires are at alternate positive and negative potentials, the difference in potential between the No. 30 and one of the No. 12's will always be greater than half the difference of potential between the two No. 12s. Consequently corona on the No. 12s would start at a lower voltage when the No. 30 is excited than when it is not. Thus the apparently continuous corona on the No. 12s in the case cited would probably be found to exist on the positive half-waves only. The cessation of the corona on the No. 30 when the alternating voltage is applied to the No. 12's is due to the fact that its initial high value of negative potential is considerably lowered when it is brought into the neutral plane of zero potential due to the two No. 12's, subjected to a difference of potential several times that applied to the No. 30.

That the presence of a greater or less number of ions has no influence on the voltage at which corona starts is evidenced by the fact that corona with descending voltages ceases at the value at which it begins as shown in my paper referred to above. This is true for the actual measured voltage at which corona begins, and also for the values at which it starts and ends on the voltage wave when the voltage is well above the corona starting value. But I have recently performed a very conclusive experiment on this point: The region around a discharging wire was subjected to a copious supply of Roentgen rays, one of the most powerful ionizing agents which may be found, and in this instance causing the discharge of a crude laboratory electroscope at great distance. Absolutely no difference in the voltage at which corona started was caused by subjecting the discharging wire to this influence.

It is a pleasure to note Professor Ryan's adherence to the ionization theory as the means by which we may hope to arrive at a satisfactory solution of these difficult questions. Engineers and engineering schools can no longer afford to disregard the important instrument which this theory offers. High voltage problems are too near to the undiscovered country for the engineer to brush aside the helping hand the physicist is offering him. It is a poor commentary on our Institute if a laboratory worker is belittled or put on the defensive. Careful research, in which conditions are controlled and admitted one by one, have been proven time and time again to be the only means by which a final understanding and economic handling of these and similar phenomena may be reached.

Erich Hausmann: The only limitation at present to increased voltages on aerial energy-transmission circuits is offered by the electric strength of air. The former limitation, imposed by insulation difficulties in high-voltage transformers and in the line itself, no longer exists; for 250,000-volt transformers of large capacity are now available, and the introduction of suspension-type insulators of several units insures good line insulation under extreme weather conditions, the number of such units increasing with the operating voltage.

The critical voltage at which power loss begins through the atmosphere between two clean power-transmission conductors of D inches diameter and spaced d inches apart interaxially has been expressed by the writer[1] by the following empirical equation which embodies the researches of Ryan,[2] Whitehead[3] and Watson[4]:

$$E_m = 47.8\ D^{0 \cdot 8} \log_\epsilon \frac{d}{D} \text{ kilovolts} \qquad (1)$$

at 20 degrees centigrade and 760 mm. pressure, for wire sizes between No. 16 and No. 0000; where E_m is the maximum value of the voltage on a representative single-wire perfectly conducting earth-return circuit, or voltage to neutral. The critical voltage for conductors of given size and spacing is practically independent of conductor material, and also of the velocity and humidity of the air. As might be expected according to the electron theory, this critical voltage varies almost exactly with the density of the air. Thus, to render equation (**1**) applicable to lines under all atmospheric conditions, the following factor must be inserted therein:

$$\delta = \frac{p}{760} \cdot \frac{273+20}{273+t} = \frac{0.385\ p}{273+t}, \qquad (2)$$

where p is the pressure in mm. of mercury and t is the temperature in degrees centigrade. Consequently in higher altitudes and at high temperatures the critical voltage will be lower.

The foregoing expressions dictate the separation of aerial conductors for a given operating voltage, the size of wire being determined by the energy transmitted and from economic considerations. Let the numerical constant of equation (**1**), the atmospheric density, the crest factor (or ratio of maximum voltage to effective value), the extension factor for multiphase circuits, and the factor of safety (or ratio of critical voltage to impressed voltage), be embodied in a single coefficient K. Then solving the expression for d, there results the necessary separation between conductors for the avoidance of corona as

$$d = \frac{D}{12}\ \epsilon^{\frac{E}{K\,D^{0 \cdot 8}}}$$

or

$$d = \frac{D}{12} \left(\cosh \frac{E}{K\,D^{0 \cdot 8}} + \sinh \frac{E}{K\,D^{0 \cdot 8}}\right) \text{ feet,} \qquad (3)$$

where E is the effective voltage between conductors in kilovolts.

1. *Electrical World*, V. 56, p. 1179, 1910.
2. TRANSACTIONS A. I. E. E., V. 23, p. 101, 1904.
3. PROCEEDINGS A. I. E. E., V. 29, p. 1059, 1910.
4. *Electrician*, V. 63, p. 828; 1909; V. 64, p. 707 and 766, 1910.

As an illustration, let it be required to determine the proper distance between No. 0000 stranded conductors (0.53 inch diameter) of a 140,000-volt three-phase transmission line in a locality where the highest temperature is 35 deg. cent. and the lowest atmospheric pressure is 600 mm. Assuming an harmonic impressed electromotive force, and a factor of safety of 1.1, the value of K is

$$K = 47.8\,\frac{0.385\times 600}{273+35}\times\frac{1}{\sqrt{2}}\,\sqrt{3}\times\frac{1}{1.1} = 39.9,$$

and

$$\frac{E}{K\,D^{0.8}} = \frac{140}{39.9\times 0.602} = 5.83;$$

consequently the distance between the conductors when triangularly spaced is

$$d = \frac{0.53}{12}\times 340.359 = 15.0 \text{ feet.}$$

To realize a larger factor of safety than 1.1 as above, a much greater separation of the line wires is necessary. The influence of the factor of safety upon the corresponding distance between conductors of the line just cited is shown by the curve plotted on semi-logarithm paper in Fig. 1, all other conditions remaining unchanged. As greater separation of the conductors means more expensive towers or individual towers for each line, as well as greater outlay in securing wider right-of-way, it is customary to employ low factors of safety.

It is found by experiment that corona loss is proportional to the square of the excess voltage over the critical value and also to the frequency; thus the loss per mile in watts on a single-wire ground-return circuit is quite closely

$$P = 0.024\,f\,(E_s - E_{cr})^2, \tag{4}$$

where E_s is the voltage (effective value in kilovolts) from conductor to neutral at any point on the line distant s miles from its generator end, and E_{cr} is the effective value of the voltage at which corona appears. This equation is similar to those formulated by Dr. Steinmetz at a recent lecture in Brooklyn. On a single-phase line and on a three-phase line (for corona loss per phase) the factor $(E_s - E_{cr})^2$ is respectively four and three times as large as for a single-wire circuit.

An important consideration arises when the distant end of a transmission line is open-circuited, for then the voltage at every point on the line increases, and the potential over a considerable

portion of the circuit exceeds the critical voltage, and consequently a loss of energy ensues. This loss begins at that point where the voltage E_0 is just equal to the critical value E_{cr}, and becomes greater and greater as the far end is approached. It is well-known that the voltage at any point on an open-circuited line of length S miles, at a distance s_0 miles from the generator end, is

$$E_0 = E_g (\cosh \gamma s_0 - \sinh \gamma s_0 \tanh \gamma S), \tag{5}$$

where E_g is the effective value of the impressed electromotive force, and $\gamma = \beta + j\,\alpha$; β being the attenuation constant, and

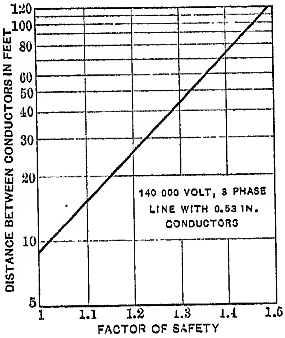


FIG. 1

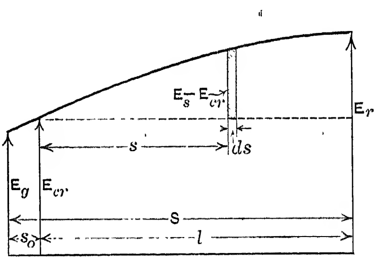


FIG. 2

α the wave-length constant, the values of which in terms of the line constants are:

$$\left.\begin{aligned} \beta &= \sqrt{\tfrac{1}{2}\left[\sqrt{(p^2 C^2 + g^2)(R^2 + p^2 L^2)} - p^2 C L + R g\right]}, \\ &\text{and} \\ \alpha &= \sqrt{\tfrac{1}{2}\left[\sqrt{(p^2 C^2 + g^2)(R^2 + p^2 L^2)} + p^2 C L - R g\right]}. \end{aligned}\right\} \tag{6}$$

The symbols C, g, L and R are respectively the capacity, leakage conductance, inductance and resistance per mile of line, and $p = 2\,\pi$ times the frequency of the electromotive force. By substituting various values of s_0 in equation (5), and plotting the corresponding values of E_0 in terms of distance, a voltage-distribution curve for the particular line will result. From this voltage-distance curve can be seen the distance from the generator end of the transmission line at which corona begins. Of course, equation (5) might be solved for s_0, but not knowing the phase of voltage E_0 at the end of this part of the

circuit, this plan leads to difficulty when applying the resulting expression to the solution of actual problems.

In order to determine the total corona loss on a representative single-wire open-circuited line, consider an element ds of the circuit, distant s miles from the point s_0 where corona begins, for which the excess voltage is $E_s - E_{cr}$ kilovolts; Fig. 2. The power loss over this elementary line section in watts is

$$d\,P = 0.024\,f\,(E_s - E_{cr})^2\,d\,s,$$

and over the entire distance $l = S - s_0$, the loss is

$$P = 0.024\,f \int_0^l (E_s - E_{cr})^2\,d\,s.$$

But from equation (5),

$$E_s = E_{cr}\,(\cosh\gamma\,s - \sinh\gamma\,s\tanh\gamma\,l);$$

therefore

$$P = 0.024\,f\,E_{cr}^2 \int_0^l (\cosh\gamma\,s - \sinh\gamma\,s\tanh\gamma\,l - 1)^2\,d\,s,$$

or

$$P = 0.024\,f\,E_{cr}^2\Big[\int_0^l \cosh^2\gamma\,s ds - 2\tanh\gamma\,l \int_0^l \sinh\gamma\,s\cosh\gamma s\,ds$$

$$+ \int_0^l ds - 2\int_0^l \cosh\gamma s\,ds + \tanh^2\gamma\,l \int_0^l \sinh^2\gamma\,s\,ds$$

$$+ 2\tanh\gamma\,l \int_0^l \sinh\gamma\,s\,ds\Big].$$

Upon integration this equation becomes

$$P = 0.012\frac{f}{\gamma}\,E_{cr}^2\Big[\sinh\gamma l\cosh\gamma l + \gamma l - \tanh\gamma l(\cosh 2\gamma l - 1) - 4\sinh\gamma l$$

$$+ \tanh^2\gamma\,l\,(\sinh\gamma\,l\cosh\gamma\,l - \gamma l) + 4\tanh\gamma\,l\,(\cosh\gamma l - 1) + 2\,\gamma\,l\Big],$$

and when simplified reduces to

$$P = 0.012\,f\,E_{cr}^2\,l\left[3 - \frac{3\tanh\gamma l}{\gamma\,l} - \tanh^2\gamma\,l\right] \qquad (7)$$

as the expression for the total corona loss in watts on an open-circuited single-wire earth-return circuit.

Referring to the 140,000-volt, 10,000-kw., 500-mile, 60-cycle, three-phase transmission line already mentioned, with No. 0000 stranded aluminum conductors placed 15 feet apart, the line constants per mile on a representative single-wire circuit which transmits one third of the total energy, are

R = 0.463 ohm (includes resistance increase due to skin effect and stranding),
L = 0.00218 henry.
C = 0.0137 microfarad.
g is negligibly small = 0.

The attenuation and wave-length constants are respectively

$$\beta = 0.000563,$$

and

$$\alpha = 0.00214.$$

from equations (6); whence

$$\gamma = 0.000563+0.00214\,j.$$

It will be observed that severe conditions are assumed in order to bring out the results more forcibly.

When the line is open circuited at the receiving end, the voltages in terms of the impressed voltage E_g at several points on the line, as determined from equation (5), are given in the following table:

Distance from generator (miles)	$\frac{E_0}{E_g}$	$\left\lvert\frac{E_0}{E_g}\right\rvert$
40	1.092 — 0.112j.	1.10
100	1.212 — 0.265j.	1.24
200	1.382 — 0.487j.	1.46
300	1.503 — 0.658j.	1.64
400	1.575 — 0.764j.	1.75
500	1.600 — 0.799j.	1.79

Thus, for a factor of safety of 1.1, the length of line over which corona appears is 460 miles. The total power loss in watts per phase into the air is therefore, from equation (7),

$$P=0.012\times 60\times \left(\frac{140\times 1.1}{\sqrt{3}}\right)^2\times 460\times[3-(4.050-1.14j.)$$
$$-(-0.990+1.78\,j.)],$$

or

$$P = 0.72\times \frac{7900}{1000}\times 460\times 0.65 = 1700 \text{ kw.}$$

which is equivalent to a current of $\frac{1700 \sqrt{3}}{140}$ or 21 amperes per phase. This current value almost equals the full-load current of $\frac{10,000}{140 \times 3}$ or 23.8 amperes which would enter this unusually long transmission line. Thus, an ammeter at the power house which supplies energy to this circuit, would indicate approximately the same current when the far end of the transmission line is open-circuited as when connected to the full load, because of the breakdown of the air near the conductors.

Samuel Sheldon: The assumption, made in this paper, that corona is initiated by the extraction of electrons from the cathode as a result of its bombardment by positive ions seems to be based (1) upon the forms of the photographic impressions around the cathode in Figs. 11 to 13, (2) upon the appearance of bright spots at the cathode in the experiments illustrated in Figs. 20 to 24*b*, (3) upon the results obtained by Earhart in 1905, (4) upon the dielectric behavior of gases, at superatmospheric pressures, and (5) upon the generally accepted explanation of the cathode glow in vacuum tubes. An assumption that corona is initiated by electrons set free from gaseous particles in the immediate vicinity of the cathode as a result of collisions with bombarding positive ions is not only consistent with the above conditions but accords with other experimental evidence not easily explained by the cathode electron theory.

The energy required to ionize a gas particle has been determined in a number of ways and is of the order $4.4 \; 10^{-11}$ ergs. The energy to set free an electron from aluminum, brass, silver, or platinum cathodes appears, from the results of E. H. Williams,[1] to be greater than this. At any rate the Nipher photographs do not enable one to differentiate as to whether the electrons, flying away from the cathode, came from inside the pin or from gas particles in the immediate vicinity.

The bright luminescent spot experiments, described in the paper, are not adequate to differentiate as to the initial source of electrons. At the pressure used, one-tenth atmospheric, the supply of gas particles in the vicinity of the cathode, although reduced, is yet ample to supply the electrons. The mean free path of a gas particle has been increased by the reduction of pressure, while the viscous retardation at a given velocity and the field intensity necessary to give ionizing energy to the positive ions has been reduced. These factors, however, are of no consequence in this connection.

Earhart's results referred to in the paper and his later results[2] taken together with those of Kinsley[3] and of Hobbs[4] using a

1. *Physical Review*, XXXI, 3, p. 216, 1910.
2. *Phil. Mag.* (6), 16, p. 48, 1908.
3. *Phil. Mag.* (6), 9, p. 692. 1905.

spherical electrode and very minute gaps of less than the wave length of sodium light, the latter being accurately measured by means of an interferometer, seemed to point strongly towards a cathode-electron initiation of discharge which entailed the characteristic differences of cathode material but was independent of the nature of the gaseous dielectric. E. H. Williams[5] considered the work of these men as open to two possible sources of error: Either the enormous electrostatic forces exerted at these minute separations pulled the electrodes into contact and thereby occasioned metallic conduction or the path of rupture was longer and different from the shortest path between electrodes. With apparatus of special rigidity he made new determinations and found that the path of discharge was not along the shortest distance, that electrode material had no influence upon the discharge-potential, that ionization of the gas reduced the discharge-potential, that the nature of the discharge for very short distances is the same as for greater distances, and that "*the presence of moisture lowers the discharge potential for very short as well as for greater distances.*" The value derived from Earhart's results, at the bottom of page 29 of the paper, is far too large if the discharge occurred as was the case with Williams—and it would be unsafe to base any conclusions upon the given value.

The dielectric behavior of gases at superatmospheric pressures is interesting and, if it were not for Fig. 17*b*, might perhaps be easily explained on the basis of initial gas ionization. This figure is not referred to in the text, differs materially in general shape from Fig. 18 although both refer to carbon dioxide, and seems to be based upon Fig. 2 in *The Electric Journal* paper. The individual observations therein given would seem to warrant a drawing of the curve so as to omit the hump which differentiates it from Fig. 18 in this paper. Assume such to be the case. The ionization of a gas particle probably either consists in the withdrawing of an electron from an atom or accompanies gaseous dissociation. If no assisting collision energy were available, it would still be possible to ionize, if the particle were placed in an electric field of sufficient intensity. A very rough estimate of the latter in the case of atom-ionization has been given as 10^9 volts per centimeter. It is possibly dependent upon the valency. The table of insulating values of various gases, quoted from Wolf in *The Electric Journal* article, indicates that the ionizing field intensity increases with change of gas to one succeeding in the following list: hydrogen, oxygen, nitrogen, carbon dioxide. The corresponding molecular bonds are respectively one, two, three and four. If now one of these gases, such as carbon dioxide, be subjected to an increasing field intensity, two ionizing agencies will contribute energy, collision with antecedent ions and opposed ionic displacement in the gas particle. At at-

4. *Phil. Mag.* (6), 10, p. 617, 1905.
5. *Phys. Rev. Lc.*

mospheric pressure the former is predominant. As the pressure is increased the mean free path is diminished and as a result the critical field intensity is raised. The proportion of the ionizing energy contributed by the second agency is thereby increased. After the pressure has been sufficiently raised the energy of collision becomes a negligible factor and the rupturing voltage remains constant. The curves for air, however, certainly have a hump at a pressure of about 10 atmospheres. But air is a mixture of oxygen and nitrogen with some other gases in small quantities. Furthermore the formation of ozone in comparatively low field intensities and of nitric oxide at higher intensities indicate that the former is due to the dissociation of oxygen and the latter to the subsequent dissociation of nitrogen. A consideration of the possible relations between restraining forces and displacements in the atom and molecule, which is beyond the scope of this discussion, indicates that the initiation of the hump accompanies the initial ionization of the nitrogen of the air.

The explanation offered in the paper for the general shape of these curves, namely a copious emission of electrons from the cathode because of the great transition field intensity, is not in accord with the well-known fact that with very high vacua no emission can be effected with the highest available voltages. The cathode emission in other vacua is the result of bombardment under the combined influences of high field intensities and very long free paths.

H. W. Fisher: Those of us who have heard or read Professor Ryan's former classic papers cannot help but rejoice that he has again presented a paper relative to corona phenomena.

His review and analysis of what others have done is most interesting. His explanation of some of the many strange results relative to sparking distances between needle points, which I presented in my St. Louis Congress paper is a source of satisfaction to me, especially in view of the fact that some of the data then given was called in to question shortly afterwards. Even as far back as 1892 or 1893, I found that with voltages of 1000 or less, the sparking distance increased with the sharpness of the needle points, and that at 6000 volts, the sparking distance could be increased by slightly dulling the points. Thus it seemed evident that the shape of point to produce maximum spark distance would possibly be different for every voltage. My St. Louis paper to a certain extent verified this original idea, but owing to lack of time and facilities for carrying on an elaborate investigation, I was unable to state definitely the form of points which would produce maximum spark distances at different voltages. I was able to show, however, the marked tendency towards a maximum spark distance by employing needles of different point diameters whose points had been measured with a microscope and grating and then assorted and arranged in pairs of like points. Experiments also showed that

when points of different diameters were used, the spark distances often depended on the position of the needles in the apparatus.

For instance, under certain conditions, a dull point at the handle side of the apparatus might give a greater spark distance for a certain voltage than would be obtained with the same voltage and the same sized points in reversed positions.

My object in again presenting these facts is two-fold:

1. Because in recent years, I have thought of a plan by which points of almost any small diameter can be constructed, thus making possible a rigid investigation with points decreasing in size to a fraction of a wave length of light.

With a definite and comparatively easy plan of making points of various diameters and in anticipation of an interesting and valuable set of experiments in a line of research work which has only been explored in an elementary manner. I hope someone, who has more time for this kind of study, than is permissible in commercial work, will undertake a rigid investigation of striking distances, and corona effects with both direct and alternating currents.

My plan of constructing points of various minute diameters is to employ the method used by Professor R. A. Fessenden in making the fine wire part of his liquid barretter.

A small platinum wire is first evenly coated by electrolysis with silver to a considerable diameter and then the composite wire is drawn down to a very small size which can result in a possible reduction of the diameter of the platinum wire to the one fifty thousand part of an inch. By the application of a suitable acid to the end of the duplex wire, the silver can be removed and the minute platinum wire made to extend a short distance beyond the composite wire.

By initially starting with a considerable amount of wire, pieces of wire can be cut off at different reductions in area and thus can be secured a great variety of wires of various sizes. With these, experiments can be made showing the results of tests with wires having square ends. Then by the application of a weak solution of aqua regia, the fine platinum points can be rounded off or reduced in size to a fraction of a wave length of light, and thus points of a great variety of forms can be obtained. The examination and the adjusting of these points in the spark distance apparatus would have to be done with a microscope.

Equipped thus with points of a great variety and definite shape and by using generating apparatus giving a steady e.m.f. and unaffected by external conditions, an investigation of this subject could be made which would be most interesting and instructive.

J. E. Noeggerath: It was a good plan on the part of Professor Ryan to adopt the electron theory for his discussion of corona phenomena. For although the theory may be upset some day, as just now some of the most important theoretical considerations in the field of physics are being thrown over—the existence

of ether and the permanency of matter and energy—it provides us with an excellent means to corelate facts belonging to different phases of engineering and physics, and thereby to strengthen assumptions that have to be made where sufficient experience does not yet exist.

It is interesting to note how the phenomena in vacuum tubes, upon which Professor Pupin touched, and most important experiments in regard to which were made by Dr. Weintraub, and also other experiments I had the opportunity of conducting, bring out certain facts that are related to corona phenomena, substantiating particularly the following four points:

1. High voltage required to start the ions (conductivity).
2. The continuation of conductivity at voltages lower than the starting voltage.

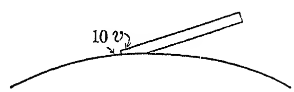


FIG. 2

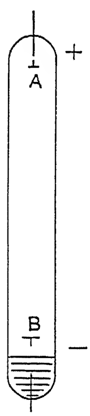


FIG. 1

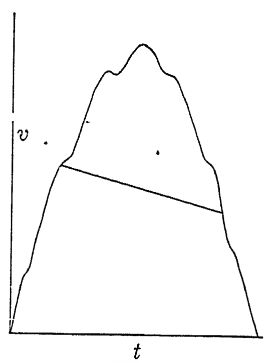


FIG. 3

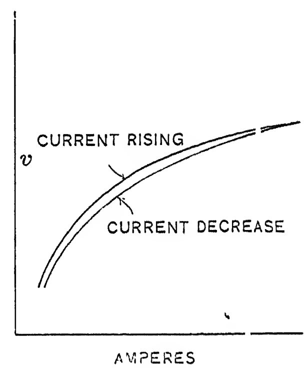


FIG. 4

3. The start of ionization at lower voltages if a supply of ions exists.
4. High stress near electrodes and low voltage gradient between them.

1 and 2. The parallel phenomena in mercury vapor lamps are well known. A simple direct current lamp, like the one shown in Fig. 1, can be started by raising the voltage to a very high value; but the current will continue to flow, if once started, at a very much lower voltage.

The same I found to be true with laminated brushes on collector-rings running up to speeds of 25,000 ft. per min., when the conditions were not favorable (Fig. 2). It took occasionally more than 10 volts to start a current, which in every case continued to flow at a voltage of the magnitude of one volt. There was no visible arc formation when this occurred.

Means for comparing the similarity of the conditions in high tension lines and brush contacts are given in Mr. Whitehead's A.I.E.E. paper of June, 1910, (Fig. 3). It shows how the conductivity through ionization continues at lower voltages once it is started. On raising, in brush contact tests, the current (when new ions have to be produced) the voltage was higher than on lowering the current at the same current density (when a supply of ions already existed) Fig. 4.

3. A good illustration of the start of ionization at lower voltages if other ions are present, is presented by Professor Ryan in Fig. 28. Similarly, if the direct current vapor lamp is connected with a side branch, as shown in Fig. 5, an artificial production of ions can be started by shaking the tube and thereby connecting the mercury in the side branch at *C* and *D*. When

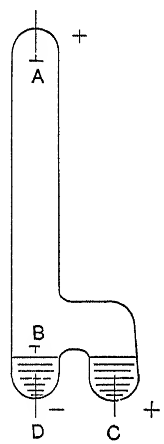


FIG. 5

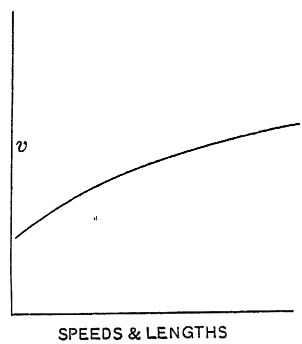


FIG. 6

the mercury is disrupted again the current continues to flow as in any arc lamp when the carbons are separated, and a stream of ions issues from the cathode. That they move in every direction can be seen from the luminosity issuing from the cathode into the main tube until it reaches the anode. Then the whole column has become a good conductor and the normal current flows.

Similarly, instead of raising the voltage, the contacts mentioned above can be put into operation by increasing the pressure upon the brush and establishing thus momentarily a metallic contact. The current will continue to flow after it has once been started, even after the pressure has been reduced to its original value.

4. The critical striking distance Professor Ryan mentions, or the thin film of high dielectric strength means that there is a high stress near the electrodes and a low voltage gradient in the

space between. The same condition exists in a vapor lamp, (as shown in Figs. 1 and 5) the stress between the points A near the anode, and the anode and points B near the cathode, and the cathode, being higher than the stress for a similar distance between points in the space between the electrodes. Thereby, it does not make much difference how close the points A and B are taken from the anode and cathode. The result is that, when the length of the mercury lamp is increased, the voltage required for a given current does not increase in proportion to the length of the tube, due to the constant or practically constant electrode voltages.

Of course such measurements cannot be taken in brush contacts because the space between ring and brush is too small (Fig. 2). However, the curves giving the relation between the voltages and lengths for arcs of a constant cross section (mercury vapor lamps) at a constant current value, are very similar to the curves showing the relation between voltage and speed in collecting systems when sufficiently high speeds are reached (when the brush elements are thrown off to a certain degree). Fig. 6 shows the general character of such curves.

The similarities between the curves of the brush contacts and the vapor lamps indicate the existence of electrode potentials also in brush contacts to which that of the intervening space is added.

With regard to the shapes of the curves, shown during the discussion, designating the various potentials between the electrodes (wires, cylinders), I do not believe that the knowledge of the phenomena in very close proximity to the electrodes is sufficiently well established to allow a proper criticism of such comparatively slight modifications.

I should prefer to express the conditions qualitatively, simply stating that there is high electric stress near the electrodes and low stress in the field between them.

To turn from these theories to practical considerations, all indications, particularly that of the comparatively small influence of the distance between wires (which is a result of the high stresses near the wires and low voltage gradient in the space between) and the effect of the maximum voltage, point to two requirements if in time higher voltages are to be used.

1. A very big increase in the distance between wires. This means earth return, which can be attained, first, by single phase transmission; second, by direct current transmission.

2. The choice of a maximum voltage as close to the effective voltage as possible, which again means direct current transmission.

An exhaustive comparison of the various systems cannot be made in the brief space allowed for this discussion, but I shall mention the most serious objection that will at once be raised; namely, that no reliable high-tension commutator or acyclic generators or motors exist for high tension direct current systems.

However, when it is considered that in a single installation, over $1,000,000 may be saved by using direct current instead of the present form of transmission, it may be worth while to spend some money on development, and in view of the vast amount of ground work done by Mr. Thury in Switzerland, it seems not improbable that high tension direct current transmission may find its field after all.

A. E. Kennelly: This paper of Professor Ryan bids fair to become as important in the literature of corona formation around high-tension conductors as his previous paper of 1904. In his 1904 paper, he showed that, under laboratory conditions, with normal air pressure and temperature, corona was produced over a wire of 4 mm. or more in diameter, when the computed electric intensity in the air reached 30 kilovolts per cm. not just at the surface of the wire, but at a distance of 1.75 mm. (0.07 inch) away from the wire; also, that for small changes of air pressure and temperature, the critical intensity increased directly with the pressure, and inversely as the temperature reckoned from absolute zero.

Since the 1904 paper was read, observations have been reported on actual aerial wires, especially by Mr. Mershon, which observations have gone to show that either corona, or brush, forms around a wire in the open air at a considerably lower (30 to 40 per cent lower) electric intensity then Professor Ryan's laboratory results would indicate.

In this paper, Professor Ryan not only discusses and confirms his earlier experimental results, in the light of modern electronic theories; but he also discusses and offers an explanation for the discrepancies between his laboratory results and the results on actual aerial lines.

He accounts for the fact that the electric intensity at the surface of a very thin wire may apparently reach 200 kilovolts per cm. without developing corona, with the aid of the electronic theory, by the proposition that a certain small radial distance is needed around the wire for electrons to develop destructive velocities at subsequent collision. The evidence for this appears to be very strong. Consequently, the normal critical intensity of 30 kilovolts per cm. is to be looked for, not at the surface of a thin wire, but at such a distance therefrom as will enable the electrons leaving the wire to attain a velocity sufficient to smash off new electrons from neutral air-particles, on collision.

He accounts for the reduction observed in critical voltage on actual overhead lines by a number of conditions that do not ordinarily present themselves in the laboratory; such as irregularities on the wires, free ions in the air, moisture, etc. We may call this the effect of "dirt," the dirt being either in the air, or on the wires. He also shows that before full corona is formed, there will be half-corona, or brush-discharge, with considerable loss of electric energy from the wire. The engineering problem is concerned with avoiding appreciable brush-discharge, and full

coronation is, from the engineering standpoint, a mere matter of degree. Between the two influences of dirt, and the partial corona or brush, a reduction factor of 72 per cent is offered by Professor Ryan as an average value to represent the ratio between the critical electric intensity over practical lines, to that found in the laboratory. A number of observations on practical lines are collected in the paper and discussed. From a practical standpoint much importance attaches to the value of this reduction-factor and to the influences which affect it.

It is noteworthy that in Fig. 1*b* of the paper the curve of critical surface-intensity under laboratory conditions, from Professor Ryan's measurements, seems to be a rectangular hyperbola, between the limits of 0.15- and 0.8-in. (0.38 and 2.03 cm.) wire-diameter,. That is, the curve between these limits corresponds to the formula:

$$e'' = 76.24 + 9.94/d'' \text{ kilovolts per inch} \quad (1)$$

or

$$e = 30.01 + 9.94/d \text{ kilovolts per cm.} \quad (2)$$

where e'' is the critical electric intensity in inch measure and e its corresponding value in cm. measure at the surface of the wire d'' is the diameter of the wire in inches, d its diameter in cm.

The agreement of this formula with the curve of Fig. 1*b* is shown by the following table:

Diam. wire, inches........	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8
e'' taken from Fig. 1*b* kv. per in..................	139	126	110	102	96	92.5	90.2	88.3
e'' computed by formula (1) kv. per in..............	142.5	125.9	109.4	101.1	96.1	92.8	90.4	88.7

For diameters below 0.15-in. (3.8 mm.), the curve departs from the hyperbola, towards a parabola, and, for very small wires, the departure is marked.

Consequently, for wires larger than 4 mm. in diameter, Professor Ryan's laboratory results indicate that we may either express the critical coronation intensity as 76.2 kilovolts per in. (30 kv. per cm.) at a striking distance of 0.07 in. (0.178 cm.) from the surface, or as $76.24 + 9.94/d''$ kilovolts per in. $(30 + 9.94/d)$ kilovolts per cm., at the surface itself. From the standpoint of the electronic theory, the constant intensity at the striking distance seems to be the fundamental conception; but there must be some curious cross-relation to bring about the hyperbolic graphical condition here indicated.

The high-voltage line loss tests appended to the paper are extremely interesting from the engineering standpoint, but not very helpful in elucidating the underlying physical laws of brush loss. The line tested runs at various altitudes, is necessarily subjected to an elevation of voltage at the far end when open

circuited, and is too long to serve as a fair test for the action of one variable at a time. The curves of Fig. 11, however, show that the apparent electrostatic capacity of the line wire rises very markedly before the brush loss becomes considerable, and the kilovolt-amperes may thus furnish a valuable practical guide to avoid kilowatt brush loss.

F. W. Peek, Jr.: Corona was first seriously investigated with the use of the visual critical point and sparking point as reference. This is recorded in classical papers by Steinmetz, Ryan, and others. On clean parallel conductors the visual critical point is very definite. Experiments show that the apparent dielectric strength of the air is greater around small conductors than larger conductors. This was first explained by assuming that a thin film of condensed air surrounded conductors. If this were so one would expect a greater rupturing gradient for the air surrounding the very dense metals, than for that surrounding the very light metals. Experiments show that this is not the case. Looking farther; in a paper by Hayden and Steinmetz at the last Annual Convention it was shown that definite energy as well as potential is necessary to rupture insulation. This makes it unnecessary to assume the condensed air film. Professor Ryan has also applied the ionization theory here.

Together with the visual tests it is seen to be important to study the phenomenon by energy measurements. This was early recognized and has been done by many investigators. These energy measurements are difficult to make because of the low power factor and high potential. To get accurate and reliable results, then, it is necessary to make measurements directly on the line, eliminating the transformer losses from consideration. This has been done in some very extensive investigations that we have carried on for the past year. It is impossible to go into detail on the methods and data, in this discussion, as it is hoped to present this soon in an extensive paper. A few points will be considered that have a bearing upon the present discussion.

A line of sufficient length to get good wattmeter readings was erected. The conductors were supported by suspension insulators on metal towers, representing standard transmission practice. An approximate sine wave voltage up to 250,000 was available. If voltage is applied to the line at night so that we can note the luminous effect, and wattmeter readings are taken we see at a certain point very low loss readings, which gradually increase with the increase in voltage; localized streamers and corona soon appear at points. The watt increase is still gradual. Slowly raising the voltage, the *visual critical point* is reached. The effect is striking. Corona suddenly jumps out, as it were, all over the line. The line immediately becomes noisy and the loss increases very rapidly with the increase in voltage. The first localized streamers are caused by " dirt," irregularities, or local ionization as described by Professor Ryan. Plotting volts

and watts we have a curve with a rather wide knee. Investigating this curve we find that the power loss above the knee may be represented thus:

$$p = cf\,(e - e_0)^2 \qquad (1)$$

where p = watt loss, e = line volts, c is a term varying with capacity, and wave shape, f = frequency. e_0 is the *curve critical voltage.* This voltage is considerably below the *visual critical voltage* for small conductors, and approaches the *visual critical voltage*, for large conductors. If now we subtract p values from

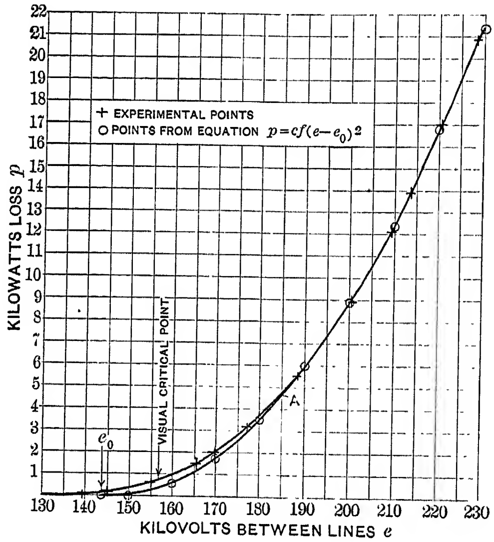


FIG. 1.—Corona loss curve

the actual experimental values we obtain a residual at the lower voltages. This residual is apparently represented by the probability curve, that is,

$$p_1 = d\,\epsilon^{-k\,(e_0 - e)^2} \qquad (2)$$

This expresses the excess loss at the low voltages due to accidental cause, namely, "dirt" spots.

Now if we look at Fig. 1 for a moment the above steps can be followed on the curve. At 140 kilovolts there is a slight loss—localized corona. At 144 kilovolts, e_0, the *curve critical voltage* is reached. Still higher, at 157 kilovolts, we have the *visual critical point.* Fig. 2 shows the line at 200,000 volts.

An interesting point I might note here. Values of $1/e_0$ were

taken for a given wire and spacing and plotted against corresponding temperatures. The temperature range was from —13 to 22 deg. cent. The plotted points were in a straight line. This line was extended and cut the temperature axis approximately at —273 deg. cent. Thus absolute zero was determined by corona measurements.

Of important bearing on the ionization theory, and a confirmation of Professor Ryan's view of "vapor products" is the effect of falling rain and snow on e_0. Snow flakes are known to carry considerable charges. Tests made while snow is actually falling show a marked decrease in the voltage at which corona loss starts, and very much greater loss than the corresponding no-snow loss.

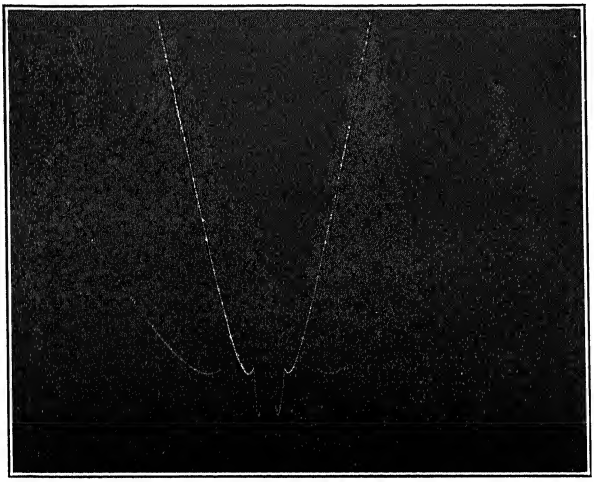


FIG. 2.—Corona on transmission line—No. 3/0 cable, 10-ft. spacing, 200,000 volts

Tests made during one rain storm—a thick misty precipitation —showed a slight, but not serious loss increase. These weather factors should be taken seriously into account in the design of transmission lines. Another effect which has bearing on the theory of Professor Ryan is that of smoke. While one set of tests were being made the wind was in the direction to carry considerable smoke from a factory power house to the line. The losses were greatly increased.

George L. Hoxie: The discussion has developed an apparent wide difference of opinion on the utility of the electron theory. Perhaps this difference of opinion is not so great as it appears. On the one hand there is full recognition of the "epoch making" character, as Dr. Pupin has expressed it, of the electron theory.

On the other hand Dr. Steinmetz refuses to concede the mechanical plausibility of the theory, or its value in predicting physical results. As to the latter time will decide. The former objection, that as a mechanical explanation the theory does not seem plausible, and that in the past the theory has been changed from time to time to fit newly discovered experimental facts, does not to my mind seem to be a very strong indictment of the theory or of its practical value, and possibly was not meant to be such.

The human mind must reason by analogies. To find, not perhaps an *explanation*, but a lucid *description*, of electrical facts, we always resort to some sort of analogy. Thus for years it has been customary to liken an electric current to a water flow in a closed circuit, and to compare certain electric properties to the pressure, volume, and inertia, of water. We have thought in terms of this analogy so constantly that no one arises to say that very likely the term "current" as applied to electricity is meaningless, that it is very improbable that a "quantity" of any tangible substance flows in a wire, or piles up on condenser plates, or acts in the other ways in which we constantly assume that electricity acts. These assumptions are in fact merely a matter of language. It would be impossible to describe electric phenomena, or to teach electrical engineering, without devising a language in which we may talk, and this language must be similar to that in which we speak of more tangible things, even though it be utterly misleading (of course we do not know if it is) if taken in its literal sense as applied to electricity.

Now we find that newly discovered facts, radio-activity, corona effects, etc., etc., demand that we enrich the conventional language with which we describe phenomena. We must therefore have conventional terms, electrons, ions, atoms, molecules, etc., and in order to use these terms so that they may convey some meaning, and always the same meaning, we have a theory. Necessarily the theory will imply mechanical analogies to things that we can see and examine. The theory must, however, be adequate to explain all known facts, and to predict with a considerable degree of accuracy various kinds of phenomena in advance of their occurrence. These requirements are what make the construction of a great new theory like the electron theory so enormously difficult, and make it so valuable or "epoch making" after it has been laboriously put together, tested, modified to fit new data, worked over by dozens or perhaps by hundreds, of brilliant scientists, and finally so perfected that it describes in a consistent language all known physical phenomena, and is reduced to mathematics so that we may "weigh" and "measure" and compute the "velocity" of the various figments of the imagination that we use; and may take a concrete example like a projected transmission line and, by the use of the theory and its mathematics, predict performance with substantial accuracy. It does not matter in the least that the

theory may not be really true. The theory is nevertheless indispensible until a better one be produced.

The only danger in a full acceptance of any reasonable theory is, as I believe was first pointed out by Tyndall, that a theory may receive such a weight of authoritative support that a later experimenter may refuse to credit his own results if they seem to overthrow the previously accepted theory, and thus the weight of authority may retard progress, and has in some instances, done so. Sir Isaac Newton developed the corpuscular theory of light, and no one can doubt that that theory was at the time a very valuable aid to the study of light. It was indispensible at the time. Yet there came a time when the weight of Newton's name held back the acceptance of the wave theory after experiments had shown the inadequacy of the corpuscular theory.

We should recognize the fact that no human theory is likely to be completely accurate. I am inclined to suspect that if some superhuman intelligence were to give us the complete solution of the problem of matter, electricity, gravity, light, etc., our minds might not have the capacity to understand. However that may be, our imperfect theories have always been valuable—in fact necessary—to study and progress. When a wealth of new experimental facts discloses a need for some new theory, and the physicists produce a theory that furnishes a possible explanation for all observed phenomena, and a reliable means of predicting new phenomena, we should either produce a better theory, or gratefully accept and use that of the physicists.

The members of the Institute owe a great debt to Professor Ryan for making the electron theory useful to the engineer. It is safe to predict that the physicist also will find this paper of Professor Ryan's constantly valuable for reference. It is seldom that we have a paper of such value.

A. B. Hendricks, Jr.: In the summers of 1903-04 there was carried out at Pittsfield, Mass., under my direction, a series of measurements of corona losses on an experimental high-tension transmission line. These were probably the most elaborate and accurate determinations that had been made up to that time. We used a single-phase experimental line 800 ft. long supported by five pairs of poles and umbrella type insulators of the largest size (about 14 in. diameter).

The following determinations were made:

Variation of loss with

1. Voltage, to 160 kilovolts effective.
2. Diameter of conductor, using copper wires 0.064 and 0.182 in. diameter, galvanized iron cable $\frac{5}{8}$ in. diameter and aluminum cable 0.8 in. diameter.
3. Distance between wires 2, 3, 4, 5, 6, 8 and 10 ft.
4. Frequency, measured at 43 and 59 cycles.
5. Atmospheric conditions, showing general effect of fair weather and rain.

The line current was also carefully measured and the critical

point for current and loss found to occur at the same voltage and to mark the beginning of loud hissing of the discharge, and in some cases of violent vibration of the conductors. The corona was not observed since the tests were made by day-light.

A typical curve sheet is shown in Fig. 1. The breaks in curves are due to a change in number of high tension transformers used in series, with resulting change in generator load, excitation and wave form. As shown, a power factor up to 0.45 was reached.

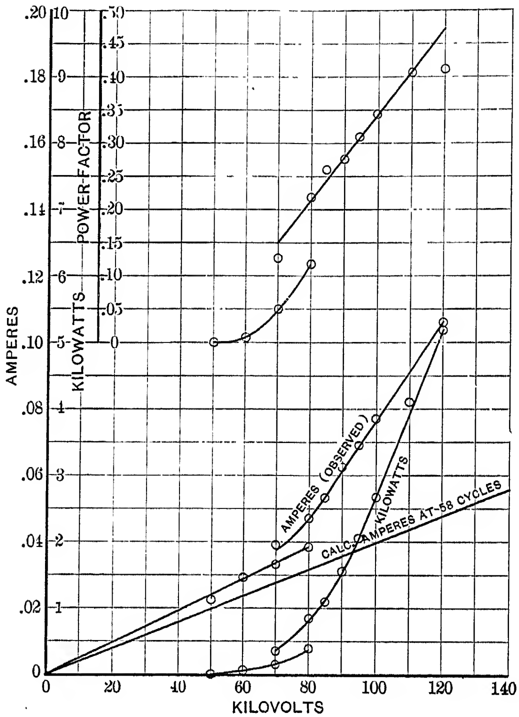


FIG. 1.—Typical curve sheet—variation of loss, current and power factor with voltage for 0.182-in. wires 4 ft. apart—800-ft. line at 58 cycles

Fig. 2 shows variation of loss for conductors 0.064 in. to 0.8 in. diameter, 2 ft. apart, from 70,000 to 130,000 volts.

Fig. 3 shows variation of loss for 0.182-in. wires 2, 3, 4, 5, 6, 8 and 10 ft. apart.

Fig. 4 shows variation of loss for 0.064-in. wires 2 ft. apart at 43 and 59 cycles.

Fig. 5 shows variation of loss for 0.064-in. 0.063 in. wires 6 ft. apart in fair weather and in rain.

In all of these measurements the current was determined by a hot wire ammeter inserted directly into the high-tension line, while the loss was indicated on a wattmeter in generating circuit, thus requiring subtraction of transformer losses from the instrument reading.

Four 40,000-volt transformers and two intermediate insulating transformers were used and great accuracy in results was impossible of attainment especially at the lower losses.

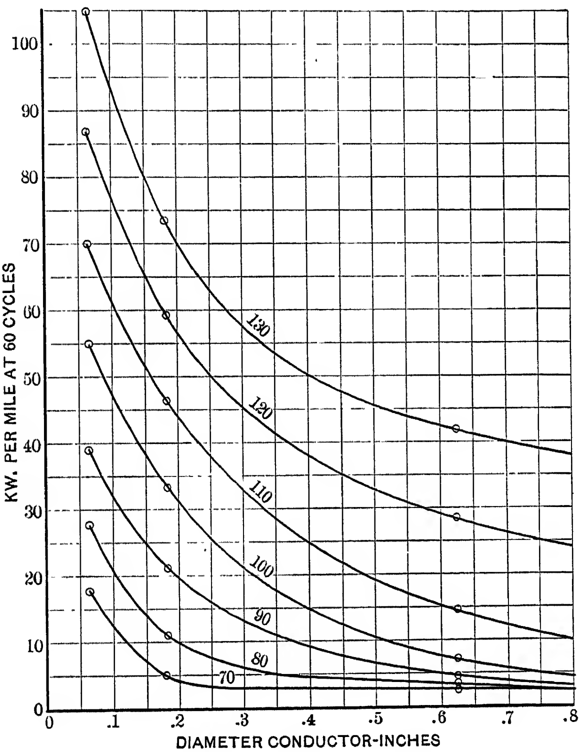


FIG. 2.—Variation of loss with diameter of conductor for wires 0.064 in. to 0.800 in. diameter—2 ft. apart—from 70,000 to 130,000 volts

This difficulty in making accurate measurements led to the design and construction of a new type of high tension transformer especially adapted to this work. In accordance with the suggestion of Dr. C. P. Steinmetz the ammeter and wattmeter are connected at the grounded neutral point of the high tension winding and measure the losses directly with high accuracy.

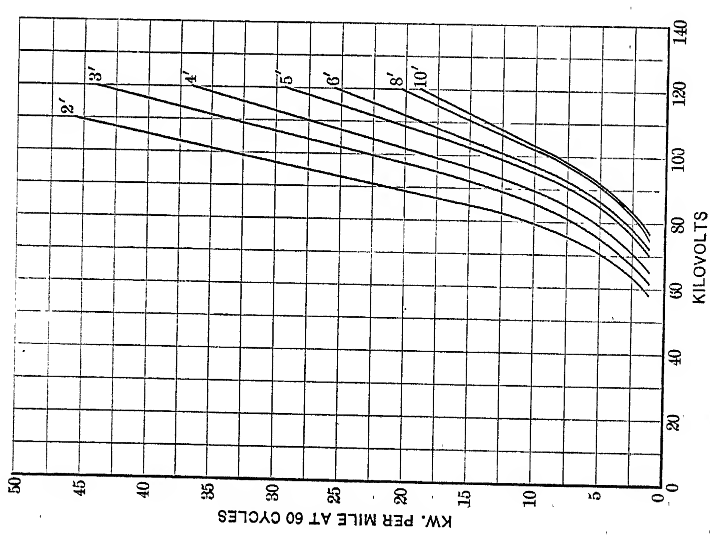


FIG. 3.—Variation of loss with distance between wires for 0.182-in. wires 2, 3, 4, 5, 6, 8 and 10 ft. apart

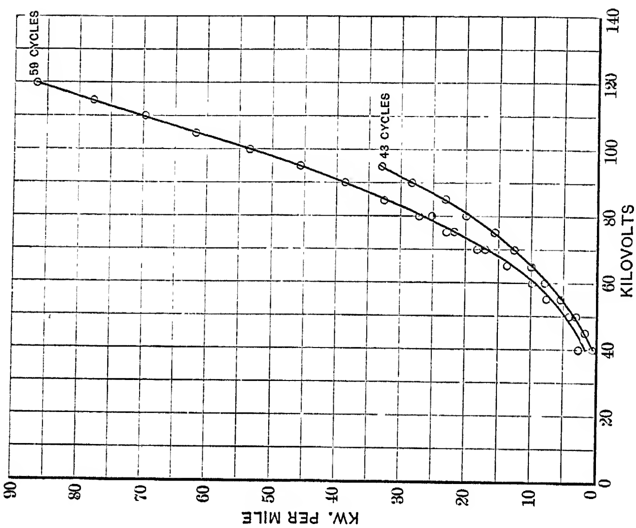


FIG. 4.—Variation of loss with frequency for 0.064-in. wires—2 ft. apart— at 43 and 59 cycles

This transformer and method is now being used by Dr. Steinmetz in a most elaborate series of new determinations, the results of which will undoubtedly be presented to this society.

As the results of my own determinations have never been pub-

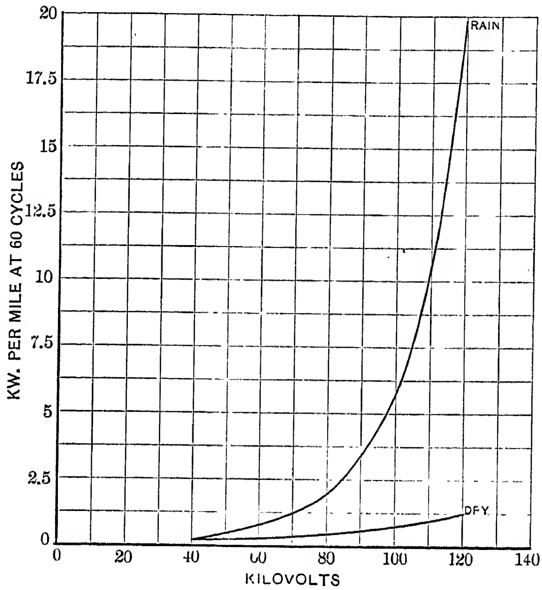


FIG. 5.—Variation of loss in fair weather and in rain for 0.064-in. wires—6 ft. apart

lished, they are referred to at this time because of the wide range of conditions covered, the accuracy of the results, and the very early date at which the measurements were made.

J. A. Koontz: Dr. Sheldon has referred to the difference of opinion in regard to the short spark discharges in air or other gases. By short spark discharge I mean the sparking distance that is less than 11.8×10^{-5} in. $(3 \times 10^{-4}$ cm.) *i.e.*, the distance which is so small that collision ionization is no longer effective.

The results of E. H. Williams[1] are quite different from those obtained by other experimenters. I cannot see, however, wherein his apparatus has superior rigidity nor that he employed as great care and precision as Professor Kinsley did[2]. I believe the work of Williams is open to at least two sources of error.

First, the voltage used to determine zeros was too high.

Second, the contacts were so highly polished that they were covered with a surface film and doubtless the distances from metal to metal, were somewhat greater than the interferom-

1. *Physical Review*, XXXI, 3, p. 216, 1910.
2. *Phil. Mag.*, (6) (9) p, 692, 1905.

eter indicated. These films may have behaved as solid dielectrics.

To follow out these short spark discharge phenomena more clearly for my own satisfaction I used the following simple apparatus: Two hemispherical, chemically pure silver electrodes were rigidly mounted on a good micrometer gauge. A pointer of about one foot in length was fastened to the micrometer head. Two mirrors were mounted, one on the frame and the other on the adjusting head of the micrometer gauge so that they would reflect two images of the same scale one directly above the other in a reading telescope, permitting accurate observation of minute changes in the micrometer gauge setting. The pointer was adjustable by means of a long lever. The zero was determined with a galvanometer using about one-thousandth of a volt. When the direct current pressure was applied a voltmeter was connected in series with the gap to measure the rupturing voltages and to limit the flow of current. See diagram of con-

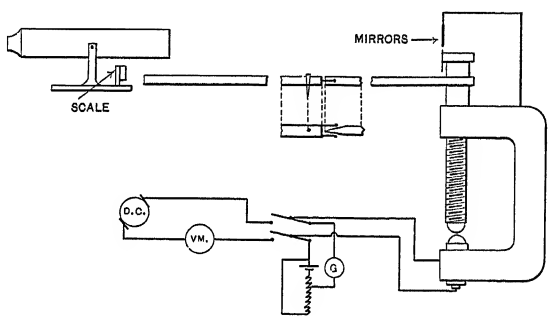


FIG. 1

nections Fig. 1. The electrodes were first polished then cleaned with cyanide and finally thoroughly washed with distilled water, so as to eliminate surface films.

The zero could be determined to approximately one millionth of an inch by the making or breaking of contact as shown by the galvanometer. It is difficult to determine the exact length of a gap when working with these minute distances because of the peculiar way in which the metallic particles act when subjected to the electric forces, due to the formation of metallic bridges or coherence wires.

When clean metallic surfaces are pressed together the movement of the gauge from a good low resistance contact to a break of contact, *i.e.*, from 0.1 ohm to ∞, is about 11.8×10^{-7} in. (30×10^{-7} cm.). Now if we separate the electrodes about 40×10^{-7} in. (100×10^{-7} cm.) and force a few milliamperes of current across the gap, the surfaces will cohere, *i.e.*, a low resistance metallic bridge will connect them. If the surfaces are then

slowly separated the resistance of the bridge will gradually increase and with care they can be separated to a relatively great distance before the coherence will again rupture. The accompanying coherence-resistance curve is taken from Kinsley's report[3] and is quite characteristic of my own results. See Fig. 2. Kinsley, working on the assumption that the coherence wires were of pure platinum, iridio platinum contacts being used, figured the diameter to be 4.4×10^{-5} cm. when $R=2$ ohms. He said therefore that we need not be surprised at our failure to observe with the microscope any evidence of coherence.

Dr. Sheldon refers to Williams' conclusion[4] that moisture lowers the discharge potential for short distances. Williams obtained for his minimum spark voltage 372 volts for dry air while physicists in general obtain correspondingly 350 volts. Williams introduces moisture and succeeds in getting the value

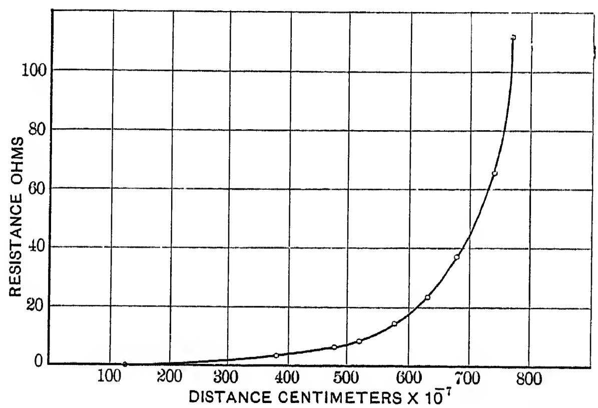


FIG. 2

of 350 volts and therefore concludes that the other physicists did not dry the air properly. Nevertheless, Kinsley even went so far as to compare the effects of various drying agents. When considering the many difficulties and wide variations obtained in such observations I do not think we are justified in drawing conclusions as to the effect of moisture from the results of Williams.

The average results of quite a number of my own observations of short gap rupturing voltages are plotted in Fig. 3. The results were obtained by the apparatus previously mentioned, no attempt being made to dry the air., The mean of the plotted results gives a value of 2,700 kilovolts per in. Earhart[5], Kinsley[6]

3. *Phil. Mag.*, (6) 9, p. 692, 1905.
4. *Physical Review*, XXXI, 3, p. 216, 1910.
5. *Phil. Mag.*, (6) 16, p. 48, 1908.
6. *Phil. Mag.*, (6) 9, p. 692, 1905.

and Hobbs[7] obtained a value of 2,500 kilovolts per in. Kinsley obtained values below and above 2,500 kilovolts per in., depending upon the treatment the electrodes received, the drying agent used, etc.

Kinsley came to the conclusion that there is a change in the form of the carriers of the electricity when dealing with distances less than 3×10^{-4} cm. J. J. Thompson[8] holds the view that in these short spark discharges the electrons are dragged out of the metal electrode by the electric field and that ionization by collision is absent.

My own experiments leave no doubt in my mind as to the essential integrity of the Earhart-Kinsley-Hobbs results.

Such thin films of air will rupture under an electric stress of about 2,500 kilovolts per in. (1000 kilovolts per cm.).

The ruptures develop coherence having in itself many interesting properties.

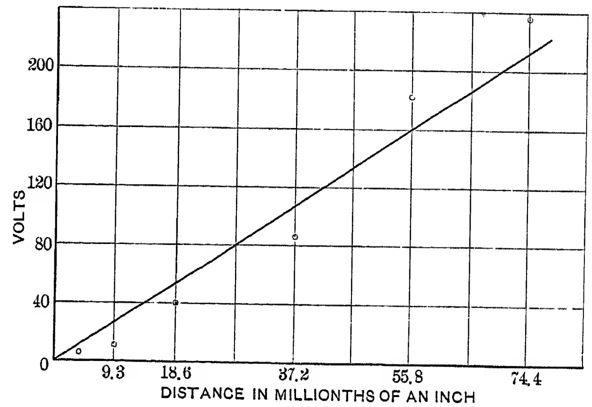


FIG. 3

The results of the various sorts obtained are of such a character and so concordant as to preclude the assumption that they are due to contacts resulting from the electric forces and the elasticity of the apparatus.

C. E. Bennett: In explanation of corona formation in oil and of the difference in corona loss from hard and soft drawn wires, Professor Ryan uses the theory of emission of electrons from the metal as suggested by Thomson to explain the experiments of Erhart and others, on short spark gaps. It seems highly probable that these results were invalidated by lack of rigidity of their apparatus, since it is difficult to secure a mounting which, under electrostatic stresses will not bend as much as

7. *Phil. Mag.*, (6) 10, p. 617, 1905.
8. Conduction of Electricity through Gases, Second Edition, chapter XV.

0.00003 to 0.0003 cm. which is of the magnitude of the electrode distances used.

In 1908, Almy[9] repeated the experiments showing the actual bringing together of the electrodes under the electrostatic attraction at voltages below the minimum potential. Using more rigid apparatus and minute electrodes to decrease the attraction, he failed to find any evidence of spark discharge below the minimum potential. Williams[10] arrives at similar conclusions with a ball and plate and states that " The discharge potential for a distance between electrodes of one wave length of sodium light is the same as for five wave lengths, being in both cases the minimum potential which is 372 volts." And again, " When the distance between the electrodes is very short, 5λ or less (0.00029 cm.) the path of the discharge is not along the shortest distance. Also ionization of the gas between the electrodes lowers the discharge potential." In a research soon to be published in the *Physical Review*, Williams shows that if the air is slightly humid the minimum potential is decreased from 372 to 292 volts.

All these experiments seem to indicate that metal electrodes even under conditions of extreme nearness, do not give out electrons in quantities sufficient to cause spark discharge, otherwise the potential would decrease with the distance, discharge would be at the nearest point, and would not be dependent upon the degree of ionization or moisture in the intervening gas. Experiments in oil point in the same direction. We have long been familiar with the way in which dielectric strength is lowered by very small amounts of water and moderate amounts of carbon. In our laboratory experiments, we have been especially impressed by the same effect with extremely minute bubbles of air, the lowering of dielectric strength, at least in the case of water and air, being out of all proportion to the quantity of foreign matter present. Published experimental data seems too meagre as yet to permit more than a guess as to whether this is a matter of electrolytic or gaseous ionization, mechanical alignment, or something else, but whatever the explanation, it seems reasonably certain that the mechanism of spark discharge must be looked for in the dielectric itself, and it therefore seems hardly necessary or desirable to turn to the metal in explanation of corona.

Harris J. Ryan: The values of a in Fig. 2 constitute the revised values of d that occur in my 1904 paper. By comparing the 1904 values of d with the corresponding values of a Fig. 2 of the present paper, it will be found that they differ appreciably for small conductors, *i.e.*, those having diameters, of 0.1 in. (0.25 mm.) and less. The differences compensate for a change from a variable to a constant corona starting stress of 76 kilovolts per in.

The preparation of the present paper was begun about two

9. *Phil. Mag.*, September, 1908.
10. *Phys. Rev.*, September, 1910.

years ago. The first work done was in connection with these critical thicknesses of the initial corona zone. The study was undertaken because Mershon in his 1908 paper made a close study of the critical corona forming distances and strains d and D that I had reported in my 1904 paper.[11] He located the curves in Fig. 48 of this paper with the values of d, D, and the conductor diameters as tabulated by me. In commenting hereon, he said: "These curves are hardly such as one would accept in connection with physical phenomena. The relations they show would appear to be entirely empirical and of a character to raise some doubt as to the necessity for the assumptions from which they result." In this, I was compelled to agree heartily, and the present study was begun to learn more about the character of the physical phenomena involved in initial corona formation.

In regard to the experiments with the small concentric cylinders Fig. 3 and the significance of one and of two pairs of cylinders in series: The purpose of these experiments was to compare the values of divergent electric stresses that cause coronas with those that cause sparks of corresponding lengths. In the coronas formed about a high-tension line, there are two divergent corona-forming fields in series; the divergent ends of these fields are adjacent, their convergent ends envelope the conductors. In many actual proportions of electrodes, these divergent and convergent ends of the fields bring about polarity effects in the migration of the electricity carriers: In an alternating circuit this might be thought to produce discrepancies between results obtained in one divergent field and those obtained in two divergent fields, back to back, in series. One needs only to recall the classical experiments, such as the stoppage of sparks between the discharge balls of an electrostatic machine (oscillations suppressed as much as possible) by introducing midway between the balls an insulated conducting plate placed at right angles to their common axis, to realize that doubts might otherwise arise as the value of the alternating spark potentials made on but one cylindrical field in air.

In regard to the vapor-product: Undoubtedly in the open atmosphere it is at all times an indirect gauge of the ionization present and, therefore, a gauge of the cause of variation of the *critical loss voltage* as distinguished from the *critical corona voltage*. The former fluctuates greatly with the supply of ions and the latter on the same account is affected but little. The fundamental cause, however, is not the presence of the aqueous vapor; it is, rather, the ions with which the vapor is associated. The relation between the critical loss voltage and the stock of ions present is direct, and aqueous vapor in the atmosphere is related to such critical loss voltage only as it is related to the stock of ions with which it is known always to be intimately

11. "High Voltage Measurements at Niagara", by Ralph D. Mershon, TRANSACTIONS A.I.E.E., Vol. XXVII, II, p. 900, Fig. 48.

associated. In consequence my claim is, with our present limited knowledge of the relation of the amount of vapor to the amount of ionization in the open atmosphere, that the ionization itself is a more direct and a more dependable gauge of the cause of the variation of the critical loss voltage that Mershon found to be related to the vapor-product than is such vapor-product of itself.

I agree fully with Mr. Faccioli that the figure of the field has most to do with discrepancies found in comparing results by experiments with results by formulas. We will no more be able to get along without experimentally determined " coefficients " in this work than the hydraulic engineer can get along without them in his work. As shown in the paper the changes in the figure of the electric field are the greatest cause for the non-agreement heretofore of the results by formulas developed in the laboratory and results by test in the open on the high-tension line. Mr. Faccioli has shown us that the ground connections did not exercise an influence in this respect in his experiments. From this it must not be inferred that the absolute potential will never enter as a factor in these matters. The absolute potential and consequent distortion of electric fields that are being dealt with must always be kept in mind.

In regard to the corona tests on the Central Colorado Co.'s lines, the remarks in my paper relating hereto are based on the data contained in the West communication. Mr. Faccioli's discussion of the same is based on his own corresponding measurements. I note that our views differ just as the data we employed are observed to differ. I firmly believe in the integrity of both sets of data. West's were obtained in the middle and later summer season, at a time when the air over the " divide " is highly electrified, and Faccioli's were obtained in the season when the Sierras, the Rockies and the intermountain region are blanketed by snow and moisture, and the electrification of the atmosphere is much diminished. In the summer in these high altitudes when the pores of the earth are open, the air always blowing eastward over the Sierras and intermountain region becomes most highly charged by the time it passes over the great divide, a matter well known in meteoralogy. This seasonal difference in the electrification of the atmosphere may well be the cause of the differences in the results obtained in the corona tests made by West and Faccioli on these lines.

I quite agree with Dr. Steinmetz that the electron theory is not far enough along in its development so that it can be employed generally to predict results. In fact it is only by the extension of knowledge by experiment that this theory is advancing. However, it must not, therefore, be expected to establish that which it needs for its own establishment. The electron theory is employed in this paper for the purpose of correlating facts giving us a basis for arranging our total knowledge so that its uses may be made more frequent and complete and so that we can more readily and safely decide between results

that are dependable and those that are discrepant. I grant most cordially that the master mind making this criticism of the electron theory has little or no need of it as yet. A profound mentality coördinates and employs all knowledge upon which it lays hold in its own way and has less need for or desire to use such a vehicle of mental association as the electron theory in its earlier stages of development. It must always be that opposition to any theory of the sort just noted is among our most valuable assets. To have diverse phenomena ordered and correlated as Dr. Steinmetz has just now done for us speaks for itself the high value of able opposition to a well-started theory.

I formulated my corona conclusions in seven brief statements to be found on the closing pages of the paper. I much prefer those to the conclusions formulated for me by Dr. Whitehead at the beginning of his discussion. The electric intensities producing sparks across cylindrical air gaps having the same proportions as initial corona zones were studied to compare their magnitudes with the electric intensities that produce such coronas. These electric intensities were found to be the same, therefore I said that corona is a glow-spark from the conductor to the air. I had no thought of calling this a corona cause. I did this to bring out the fact that coronas, glow discharges and sparks are intimately related, being fundamentally the same phenomena made to differ in form as the mechanical and electrodynamic effects of the electric carriers are made to differ through change in the physical proportions of electrodes and air gaps.

The evidences that corona covering the negative conductor is started by collision ionization produced by the outward travel of electrons from the cathode conductor surface liberated therefrom by the impact of incoming positive ions, called by the physicists canal rays, are the following:

1. In a vacuum discharge tube with its air pressure at the convenient value of 1/760 in. of mercury, the cathode ceases to discharge electrons from that portion of its surface when positively charged atoms or ions (canal rays) are not allowed to strike it.

2. In the normal atmosphere as shown by Nipher in the classical experiment of preventing the passage of strong sparks between the discharge balls of an electrostatic machine by the interposition of an insulated metal plate which prevents a larger portion of the canal rays from striking the negative discharge ball.

3. By the studies of the cathode corona a' and a'' emanating from the cathode spots b' and b'' in connection with Figs. 20, 21, 22, 23, 24*a* and *b*, and 25, in the normal atmosphere reduced to a pressure of 3 in. on the mercury column. These were spark discharges. Precisely the same though less convenient studies can be made with coronas, where one of the positive electrodes is always the enveloping air into which the collision ionization has not extended.

4. The sensitiveness of the cathode corona to any radioactive

substance at the surface of the cathode conductor known to be liberating electrons is evidence that out-going electrons at such surface promote the development of cathode corona. These effects are not found at the anode conductor because the corona there is inaugurated by incoming electrons producing collision ionization.

5. The visual characteristic difference of the coronas over the negative and positive conductors is evidence of the same character, *viz.*, that the one is started by out-going electrons in collision, and the other by incoming electrons in collision. The initial corona about the cathode conductor is of an irregular tufted, brush character and that about the anode conductor is short uniform, and flat against the conductor. (Remember that each is due to the movement of electrons in collision crossing first a cathode dark space in which the collision ionization action gathers headway resulting in the production of glow or brush. This is the reason why the negative corona is not flat against the cathode conductor and the positive corona is flat against the anode conductor. What liberates these electrons at the surface of the cathode conductor that, travelling outward, produce, by collision ionization, the cathode corona?)

Dr. Whitehead says these are not conclusive evidences that the electrons departing from the surface of the cathode conductor are liberated thereat by the impact of the incoming positive ions (canal rays). Of course, every man has the right to decide for himself when the evidence is sufficient. I hope that he can give us more evidence as to this vital point, and that will be in his estimation conclusive as to the source of the outgoing electrons which produce the corona that covers the cathode conductor. To me this evidence is not all of the kind and amount that I would like to have, nevertheless in the general circumstances of the case it is reasonably conclusive.

As to Dr. Whitehead's dissatisfaction with the experiment in connection with the No. 12 high-tension wires and the No. 30 negatively charged wire between them, Fig. 28. Doubtless there is some modification of the electric field produced by the change in the absolute potential and by the presence of the additional supply of migrating electrons. That is just the point in the experiment, the cause for my satisfaction instead of a lack thereof. That I am not alone herein is shown by the comments of Mr. Noeggerath.

If there is one thing I have emphasized strongly in my paper and in the conclusions at its close, it is that ionization by collision is the cause of corona and that the critical balanced visual corona voltage (not critical loss voltage; that is another thing) is not affected by considerable variation in the amount of antecedent ionization. Dr. Whitehead introduces his interesting and valuable experiment with Roentgen rays with comments that would lead the reader to understand that we differ as to this point. On the contrary his experiment supports in the strongest manner one of my most important conclusions.

Dr. Whitehead's statement that spark discharging intensities at electrode surfaces in the normal atmosphere under some circumstances are higher than 76 kilovolts per in. is misleading as it stands. They are higher in a uniform electric field only when the gaps are shorter than the critical gap-length, and when the electric field is divergent, convergent or both in series. In the former case the electric intensity has had to be raised by lessening the minimum distance required in which to build up the full state of collision ionization. In the latter case, besides the intensity of 76 kilovolts per in., that starts collision ionization for the longer sparks, an additional stress is required to increase the quantity of ions thus formed sufficient to produce a core. The initial transport of such core takes further toll, not through electric intensity at the conductor surface, but through added voltage which supplies the drop along the resulting spark length. Undoubtedly then one does find electric intensities at initial corona zone distances from the conductors surfaces required to produce sparks that are greater than 76 kilovolts per in. for the reason just given, a matter that was not directly brought up in the paper for it was thought to follow as a matter of course. The spark intensities referred to in the paper had to do with spark distances equal to initial corona zone thicknesses. I am glad that Dr. Whitehead has forced this emphasis of the distinction between the two classes of sparks. All this does not alter in the least the fact that a stress of 76 kilovolts per in., approximately in the normal air is sufficient to start collision ionization except at smaller than critical distances. The ionization may not be enough to produce a core and thus to develop into a spark—added intensity may be necessary for that. Great increase in conduction will promptly and certainly result in the normal atmosphere that is pervaded with a minimum stress of 76 kilovolts per in., for a distance greater than the critical distance upon slightest increase in voltage. I have never found evidence to the contrary.

In concluding my reply to Dr. Whitehead, I wish to insist cordially that there is no important difference in our understanding of these matters when we get together on terms and ways of talking about things. Naturally when I say that changes in antecedent ionization will produce corresponding changes in the *critical loss voltage*, and he understands thereby that I am referring to the *uniform balanced critical corona voltage*, that he observes in the laboratory to be unaffected by Roentgen rays he concludes that I am quite wrong and informs us so in emphatic terms, yet each has referred to a totally different thing —the only cause of the discrepancy. This of course is a difficulty quite natural in such a new subject. It will pass quickly enough. Dr. Whitehead's is the first corona paper to employ our knowledge of the behavior of electrons and the ions they produce. It is of high value on that account and because of its thorough-going integrity within its own limits.

I fully expected that the family difference among our friends the physicists, in regard to the results of Erhart, Kinsley, Hobbs and Shaw, supported by J. J. Thomson, would come up, and I hesitated at first to use Erhart's results on this account, because of the confusion that it inevitably must leave in the mind of the average reader of the TRANSACTIONS. When I found that a prominent intelligence transmission engineer in England had made practical use of the Erhart result in such proportions as to eliminate the erratic character of coherence that follows the Erhart discharge, so as to produce a marvellously successful telephone repeater, I felt that Erhart's values should be used to support my own for the intensities (2500 kilovolts per in.; 1000 kilovolts per cm.) that liberate the free electrons from a metal electrode into surrounding gas.[12] I have now gone over these papers (see Dr. Sheldon's references) and we have worked with the minute gaps, using silver electrodes, so that we might better understand the papers, especially that of Williams. It is a long story, a whole paper in itself, as to the rational cause for the family quarrel of the physicists over the point. The chief cause of the difficulty is the make-up of the actual surface of a polished metal. Such a surface has a complicated character. Erhart, Kinsley and others, with superb experimental strategy, used electrical coherence to draw some of the metal of the electrodes through the surface films so that the discharges were made to pass truly from metal to metal across distances less than one fifty-thousandth of an inch. Williams, in an otherwise beautiful work, refused such strategy, and so obtained negative results. His discharges are all collision ionization discharges in which there appears an excess voltage required to batter down the surface film produced by polishing or other treatment or condition. Mr. Noeggerath in his remarks gives independent confirmation of the existence of such surface film, likewise of the conduction by free electrons or ions across these extremely short gaps. Time does not permit, and space in the TRANSACTIONS would not permit me to take up these matters fully. I have studied them with some care and will say that in my judgment the physicists have shown that a stress of about 2500 kilovolts per in. is required to cause electrons to pass from the exposed surface of a metal electrode to a gas in which it is immersed.

Taking up Dr. Sheldon's comments on Fig. 17*b*: I introduced that chart for general interest. I found that the records were hardly clear enough to warrant a computation of the electric strain about the needle points at which the rise in kilovolts per in. against pressure per sq. in. in CO_2 ceases for the first time.

In regard to Dr. Kennelly's contribution to corona discussion:

12. The Brown Telephone Relay. S. G. Brown, The Institution of Electrical Engineers. Presented in May, 1910. Jour, 45, pp. 590–601, Sept. 1910. Also Sci. Abs. Dec. 1910 No. 1101 p. 470.

At the White Mountains Convention last July, Dr. Kennelly in discussing Dr. Whitehead's papers brought forward as a corona factor the liklihood that an ion will travel faster in a convergent than in a divergent electric field. In preparing my paper I had not noticed this perception of Dr. Kennelly's of the cause of the accumulation and retention of a stock of ions in the atmosphere in the open about the conductors of a high-tension transmission. He has clearly and strongly anticipated my own conclusion in the matter.

Mr. Peek has kindly given me the structural data pertaining to the experimental line referred to in connection with his Figs. 1. and 2. Using these for substitution in equation No. 3 of the present paper wherein the irregularity factor is taken at 0.75, the critical corona voltage is computed to be 155 kilovolts while Mr. Peek reports that the visual critical corona voltage was observed to be 157 kilovolts as an experimental check. That he found the *temperature reciprocal to critical voltage relation* at stationary barometer on the large out-door high-tension experimental line, to be rectilinear, passing through zero on the absolute scale of temperatures, is most important in the corona problem of the engineer. This corroborates on a large practical scale my laboratory conclusions of 1904, and will cause practicing engineers to have confidence in the definite corona temperature factor.

Referring to Mr. Hendrick's contribution; through a former coworker of his I have profited since the presentation of my paper, by an opportunity to look over the original series of data curve sheets from among which his Figs. 1-5 were taken. They constitute a valuable addition to our corona data collection. After allowing for the high-voltage wave form factors, they check up at all points that I have tried for integrity.

A paper presented at the 255th meeting of the American Institute of Electrical Engineers, New York, February 10, 1911.

ADVANTAGES OF UNIFIED ELECTRIC SYSTEMS COVERING LARGE TERRITORIES

BY WILLIAM B. JACKSON

A few years ago the advantages of electric light and power were considered to belong to cities and the larger towns alone, but it is becoming recognized that with properly organized companies and with plants suitably planned the benefits of electric lighting and power may be supplied at reasonable cost also in sparsely settled regions.

To provide electric light and power for a densely settled district, except in cases of very large cities, is comparatively simple, for this requires an organization and plant for a limited and homogeneous community. But for the larger possibilities of service, which means the tying together of many cities and towns, villages, and even outlying homesteads, by a great network of transmission and distribution lines, a more complex problem is presented.

To realize one of the material operating advantages of unified electric systems, the general direction of the operations of the company must be centralized, while the local characteristics and requirements of each community must be intimately considered, if the most satisfactory service is to be provided. This requires an organization controlled by exceptionally broad and discriminating engineering and commercial judgment.

Several factors tend toward making it economically possible to serve any territory from a comprehensive transmission and distribution system as a substitute for disconnected central stations located in the cities and villages. These may be here summarized as follows:

1. Saving in power house equipment made possible through

taking advantage of the diversity of different communities by serving them from the same transmission system.

2. Lower power generating cost per kilowatt-hour due to larger power plants and improved load factor.

3. Less investment in power plants per kilowatt capacity on account of larger plants as compared with smaller.

4. The possibility of decreased percentage of spare apparatus by appropriate arrangement of power plants.

5. Saving in cost made possible by centralized management, general superintendence and other general expenses.

6. The possibility of providing rural and suburban service that could not be profitably reached by a local central station.

7. The possibility of large corporations providing power service which would be too extensive for small companies to undertake.

8. The development of water powers for electric service.

The savings made available by the above may be set against the losses occasioned by the transmission transformers and lines and the cost for their current maintenance, deferred maintenance and interest on investment, to determine whether a unified system or a number of separate plants can most economically serve a territory. But it should be borne in mind that only by covering the country by electric circuits for comprehensively serving groups of cities and villages from relatively large power houses, stragetically located, is it possible to serve rural districts generally with electric light and power at reasonable cost. It is seldom economically possible to serve a rural district alone, just as it is impossible to provide electric railroad service to such a district without considering terminal cities.

The practicability of serving by electric transmission systems large territories comprising all kinds of communities, urban, suburban, and rural, was first demonstrated by hydroelectric developments from which the transmission of the power was necessary in order to obtain a market. Astonishing development has occurred in such systems since their introduction only a few years ago. It is eighteen years since the first commercial electric transmission plant in the United States using 10,000 volts or over was started at Pomona, Cal., while it was three years later when the first such plant east of the Rocky Mountains began transmitting electric power from Lowell to Grand Rapids, Mich. The transmission from Niagara Falls to Buffalo was put into operation shortly thereafter. To-day the state or

territory within which important hydroelectric transmission systems are not found is an exception. In less than fifteen years the generation of electric power from water powers and its transmission and distribution has become an important industry in almost all sections of the United States. And it has

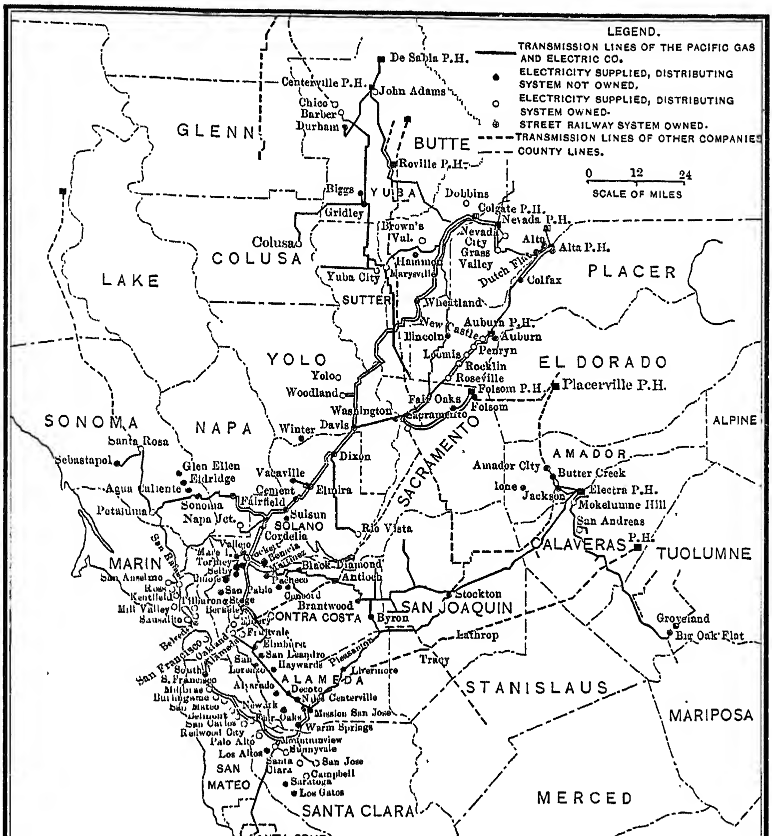


FIG. 1.—Transmission lines of the Pacific Gas & Electric Company, Central California

carried the benefits of electricity to many regions that otherwise could not be served.

The wide distribution and scope of service of our hydroelectric systems is illustrated by the following brief consideration of a few representative systems.

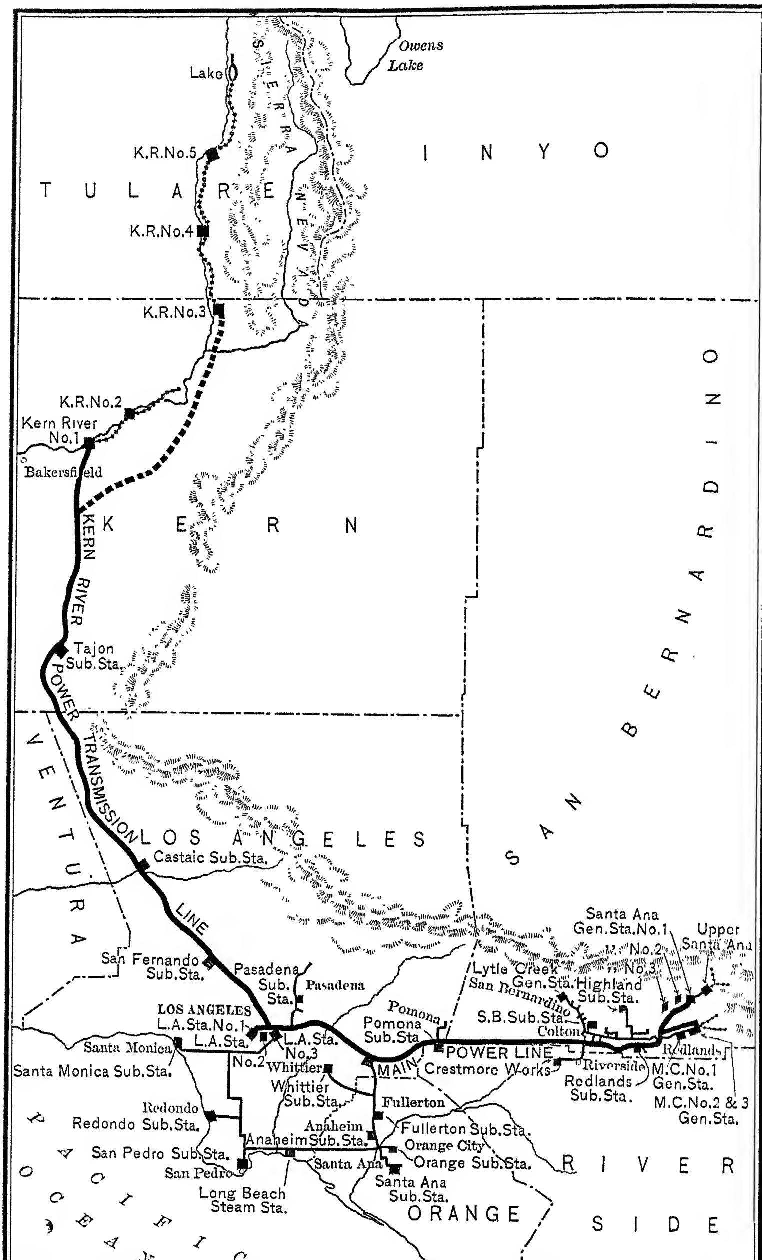


FIG. 2.—Transmission system of the Southern California Edison Company

In the region tributary to San Francisco and Sacramento the transmission and distribution system of a single company serves a district comprising fully 12,000 square miles (31,080 sq. km.), which is an area 50 per cent greater than the entire state of Massachusetts. Broadly speaking, the territory tributary to the circuits is nearly three times as great an area. The company serves more than 150 cities and villages and the greatest air-line distance between any two points on its system is over

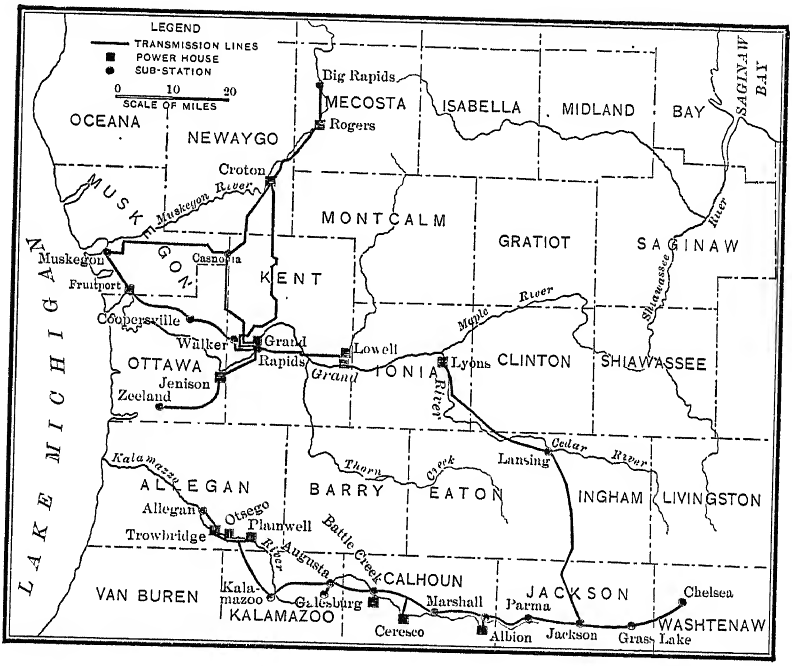


FIG. 3.—Transmission systems of the Commonwealth Power Company and the Grand Rapids—Muskegon Power Company

200 miles (321 km.), or about the distance from Niagara Falls to Utica, New York. Much of the region served could not economically receive the benefits of electric service except by some comprehensive system such as that under consideration. The extent of this system together with others in this territory are shown in Fig. 1.

The Los Angeles and Redlands district is served by two great electrical systems which cover an area of fully 1,000 square miles (2,590 sq. km.) and provide electric service throughout the

entire district, city and rural. The larger of these is shown in Fig. 2.

In the middle west, the two electric power companies in the vicinity of Grand Rapids and Battle Creek, Michigan, are good

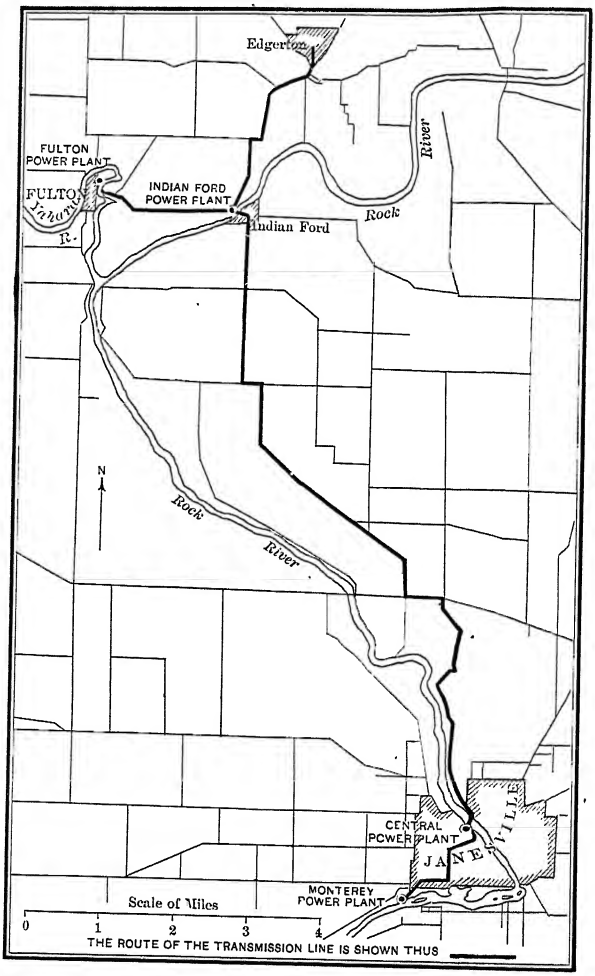


FIG. 4.—Transmission system of the Janesville Electric Company, Janesville, Wis.

examples of well developed and rapidly expanding hydroelectric systems. These serve 25 cities and villages ranging in size from 90 inhabitants to 112,000 inhabitants, twelve of the villages having populations of less than 1,250 each. These companies

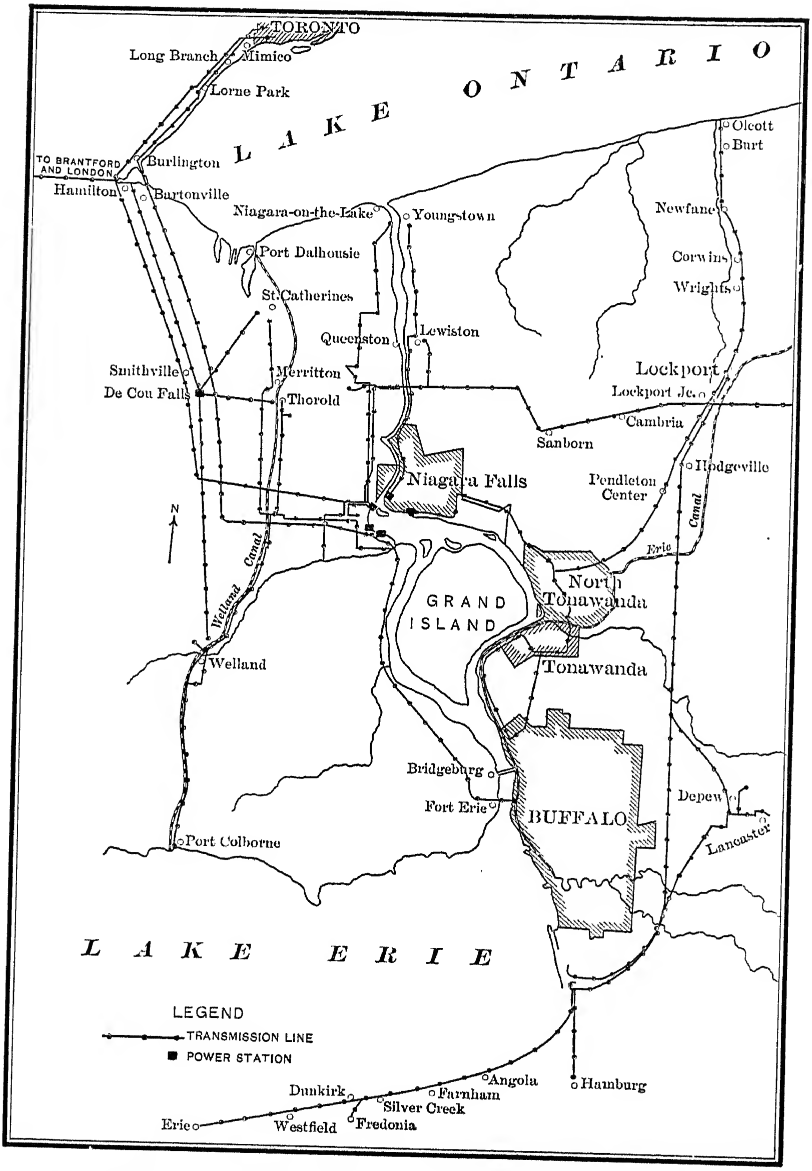


FIG. 5.—Electric transmission lines in the vicinity of Niagara Falls

also provide power for a number of interurban and city railroads. A map of the systems is shown in Fig. 3.

An interesting example of a small but rapidly expanding transmission and distribution system is that of the Janesville Electric Company in Wisconsin, which now utilizes four water powers and provides service to four cities and hamlets and some rural service. This system is shown in Fig. 4.

In Fig. 5 is shown the extensive systems of electric transmission circuits emanating from the water-power plants at Niagara Falls.

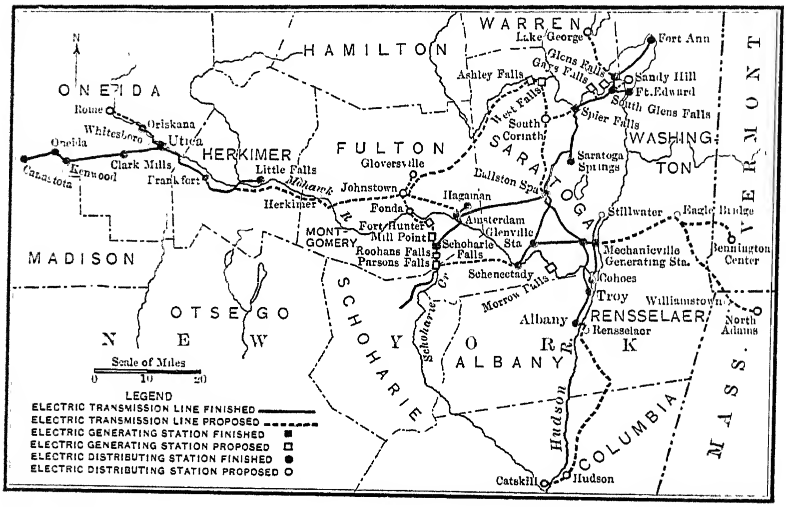


FIG. 6.—Electric transmission lines of the Hudson River Electric Power Company

In the East the effect of hydroelectric development in bringing to large territories service from single comprehensive electric systems is well illustrated by the system of the Hudson River Electric Power Company which is shown in Fig. 6. This company serves 13 cities and villages together with a large mileage of electric railroads.

In the South, the Southern Power Company has created a remarkable electric system in North and South Carolina which is shown in Fig. 7.

Fig. 8 shows a map which was the result of a somewhat extended trip of the writer over the rivers of South Carolina in

1902. Estimates were made of the available power of a large number of the shoals and falls together with the power consumed in the various cities of the state, and this map was prepared to show the possibility of a comprehensive electric system to cover the cotton mill section of South Carolina, supplied with power from the numerous water powers of the state.

Many of the companies having electric systems covering large territories have not made serious endeavor to obtain rural patronage but I believe it is safe to predict that this patronage will be more earnestly sought as time progresses, and it should be a policy of such companies to so arrange their systems and organizations that they can suitably provide the service. Hydro-

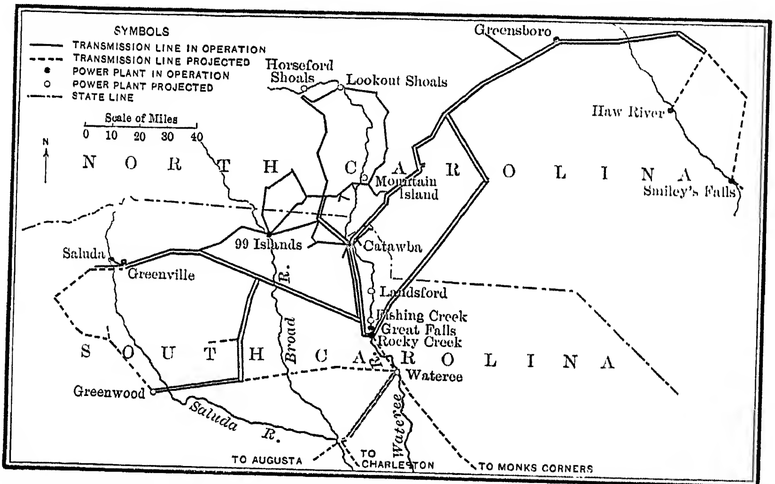


FIG. 7.—Electric transmission lines of the Southern Power Company

electric transmission companies are benefited by the advantages incident to serving numerous communities from single comprehensive transmission systems, but with them such systems grow up as a matter of necessity along with the development of the water powers, since the creation of transmission systems is necessary to the development of the water powers and the nearest markets are naturally sought for the output of the plants.

The requirements of hydroelectric transmission companies gave such impetus to the development of reliable and economical transmission methods and apparatus, that within a score of years the transmission of electric current at high voltages and for long distances has been advanced from the experimental

stage to a position of prime importance During this period equal advances have been made in methods of distributing electric light and power to widely scattered customers.

With the perfecting of electric transmission and distribution methods came consideration of the practicability of displacing small central stations by electric current transmitted from relatively large steam generating stations. With hydroelectric plants it is necessary to transmit the water-generated power from points fixed without regard to the markets, and to compete

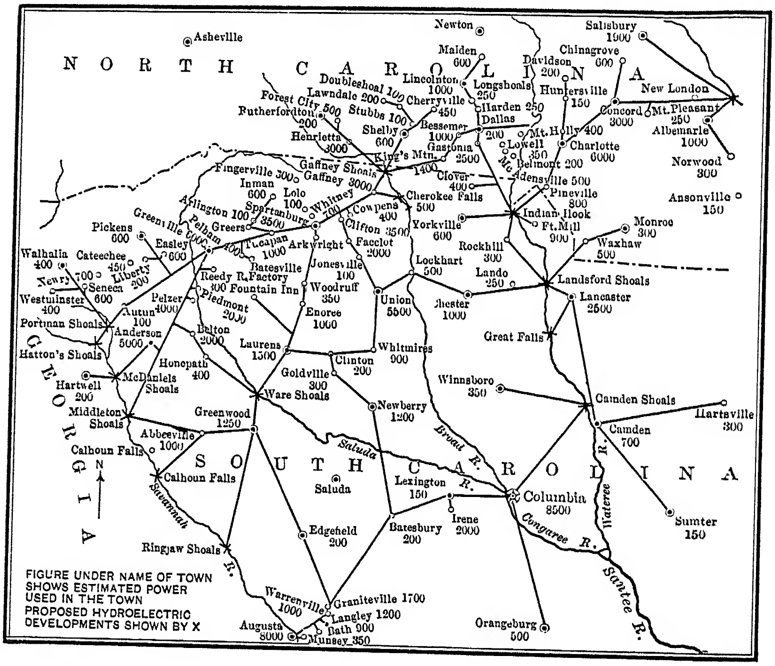


FIG. 8.—Proposed universal electric system for South Carolina

with or displace local steam powers. Much the same conditions exist with steam-electric transmission plants except that the locations of the power plants may be influenced by the locations and characters of the market.

Considerable territory is now covered by electric transmission lines receiving power from steam plants and its extent is steadily increasing. Wherever transmission lines are found, electric service should be available for the local customers; and every extension made to a transmission system should mean the open-

ing up of new districts to electric service. In the vicinity of many of our large cities and of some of our smaller ones such systems are now found.

A fine example of a well developed and rapidly expanding system, emanating from steam power plants, is that of the North Shore Electric Company which serves a district covering 1,200 square miles (3,108 sq. km.) surrounding the City of Chicago. It supplies electric current to 60 cities and towns varying in population from 27,000 to 100 people each. Nineteen of these have less than 1,000 inhabitants each, and it is doubtful if one-third of the towns could have adequate electric service were it necessary for them to depend upon local central stations for supply. A map of this system is shown in Fig. 9.

Another system, the major portion of which is fed from steam plants, is that of the Eastern Michigan Edison Co., which is a comparatively new and rapidly expanding system. It covers a territory of over 900 square miles (2,331 sq. km.) extending east and northeast from Detroit, and serves 19 towns ranging in size from 150 to 19,000 inhabitants. Only eight of these towns have a population of over 1,200 inhabitants each. This system is shown in Fig. 10.

A system that is well developed and has been steadily expanding for many years is that of the Edison Electric Illuminating Company of Boston. The company comprehensively covers the territory of Boston and its environs, extending 24 miles (38.6 km.) westward from the harbor and extending in a north and south direction 26 miles (41.8 km.) aggregating about 625 square miles (1,618 sq. km.). In addition to the corporate City of Boston, which has a population of over 670,000 inhabitants, the company serves 35 cities and towns ranging in population from 800 to 77,000 inhabitants. Of these municipalities, nine have populations of less than 2,000 people each, 26 have less than 10,000 inhabitants each, and five (besides the City of Boston) have over 25,000 inhabitants each. Many of these municipalities contain within their borders a number of villages or hamlets which are more or less distinct from each other. Much of the territory is densely populated, but the townships comprising about one-third of it have a population averaging less than 100 people per square mile. The system is shown in Fig. 11.

The above instances serve to illustrate the strides that have been made in the development of extensive transmission sys-

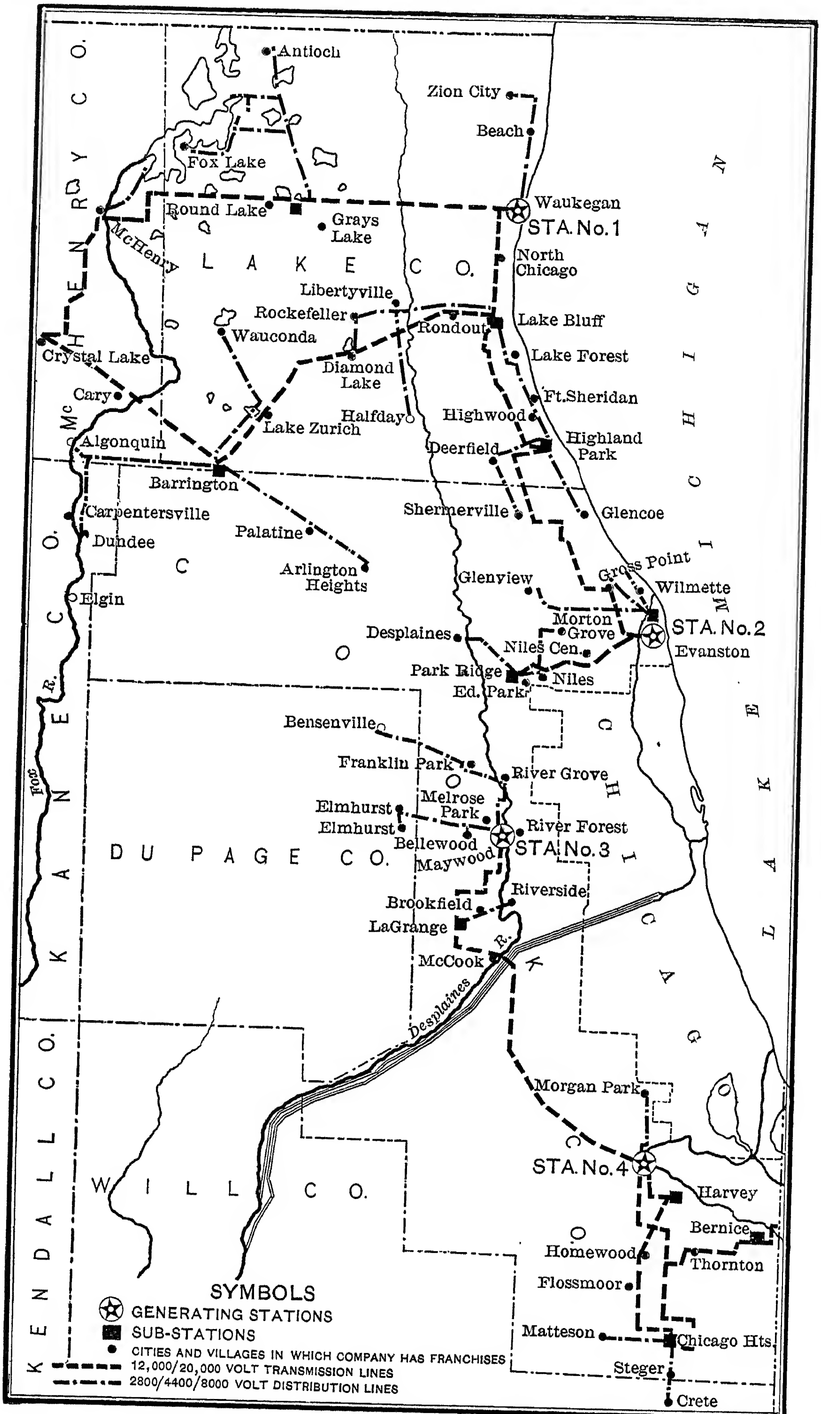


FIG. 9.—Transmission lines of the North Shore Electric Company, Chicago, Ill.

tems fed from steam plants. Considering the material progress that has been made by electric transmission and distribution companies, one may truthfully say that a start has been made toward covering the rural districts of the United States with electric circuits which should ultimately make it practicable to provide electric service to substantially all urban, suburban, and rural districts, wherever located; and excepting the possibility of some epoch making discovery, the creating of comprehensive consolidated systems of distribution appears to be the only way in which such a result can be accomplished.

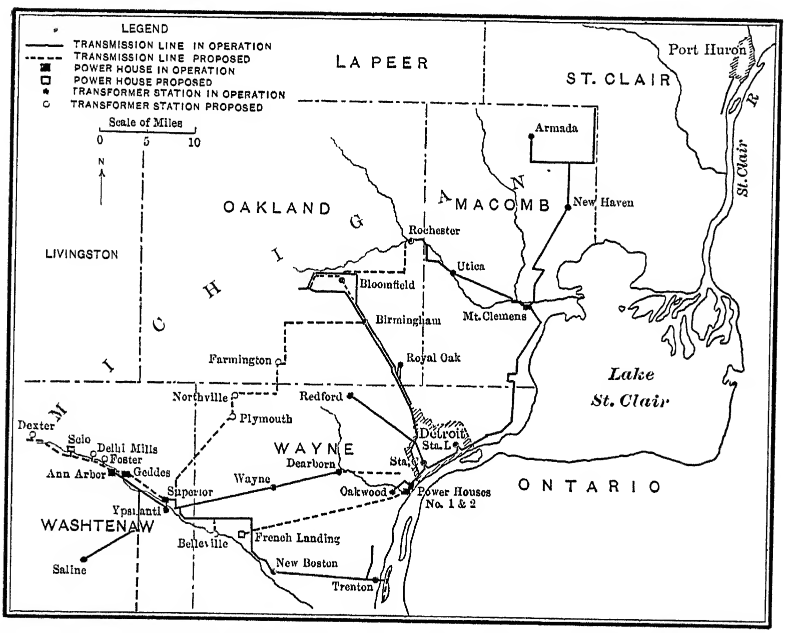


FIG. 10.—Electric transmission lines of the Eastern Michigan Edison Company

SAVING IN POWER HOUSE EQUIPMENT BY DIVERSITY FACTOR

The question of diversity factor as between various communities which are provided with electric service from a single transmission system is quite complex. By diversity factor is here meant the ratio of the sum of the maximum peak loads of separate plants which would serve the individual communities to the maximum peak load that would occur if the plants were combined. The condition may be illustrated by a consideration of the load curves of four central stations in the Northwest.

One of these, (Plant 1), serves a city of 50,000 inhabitants with mostly business and residence lighting service and has a maximum output of over 900 kw.; the second (Plant 2), serves a city of 20,000 inhabitants having a good lighting and commercial power load together with the local street railway service, and has a maximum output of 1250 kw.; the third, (Plant 3), serves an

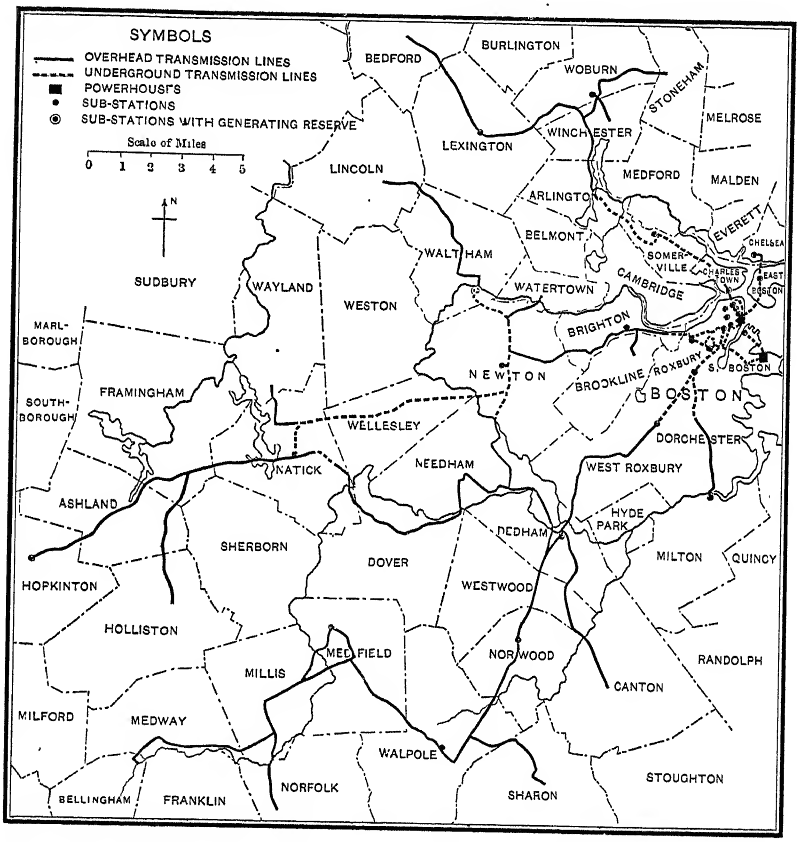


FIG. 11.—Electric transmission system of the Edison Electric Illuminating Company in Boston and vicinity

agricultural town of 4,000 inhabitants and has a maximum load of approximately 105 kw.; and the fourth, (Plant 4), provides only business lighting and power service, and has a maximum load of over 790 kw. These are highly dissimilar in their characteristics and give the following result as regards diversity factor:

	Maximum individual peaks during the year			Largest coincident peak during the year		
	Kilowatts	Date	Time	Kilowatts	Date	Time
Plant (1)......	920	Jan. 22	8 p.m.	790	Dec. 23	5 p.m.
" (2)......	1250	Nov. 12	9 a.m.	1190	"	"
" (3)......	104	Nov. 15	6 p.m.	74	"	"
" (4)......	794	Dec. 27	5 p.m.	784	"	"
Total.........	3068			2838		

There is therefore a difference of 230 kw. between the largest coincident peak and the sum of the maximum peaks, which represents a diversity factor of 1.09. This seems a surprisingly small advantage from the combination, but it would allow a corresponding reduction in machinery to carry the peak load in a unified transmission system over what would be necessary if the maximum peaks were coincident, and would correspondingly improve the load factor over the average of the separate plants. The reduction in peak here indicated is equal to more than twice the maximum load of the smallest plant referred to.

When plants (1) and (2) only are combined, the time of their largest coincident peak is the same as in the foregoing case so that for these two plants there is a difference between the coincident peak and the maximum peaks of 190 kw. and a diversity factor of 1.10. This saving in peak capacity amounts to 21 per cent of the smaller maximum peak and a combined plant would have only 79 per cent of the smaller peak added to the larger.

Considering plants (1) and (3), the greatest coincident peak is formed by 920 kw. and 89 kw. occurring at 8 p.m. on February 19, and the maximum peaks are as heretofore given. With this combination there is a saving in peak capacity of 15 kw., which leaves the diversity factor little different from unity, but amounts to about 15 per cent of the peak output of the small plant.

When plant (3) is combined with plant (2) there is a saving in peak capacity of 51 kw. which amounts to 49 per cent of the maximum load of the small plant.

Two large groups of towns, for which the aggregates of maximum peaks are about 10,000 kw., show the following diversity factors: One of the groups, which comprises towns having rather uniform characteristics, shows a diversity factor of something over 1.10, while the other group, in which the towns have diversified business characteristics, shows a diversity factor which is larger than 1.18.

All of the data I have available tend to show that diversity factor as between towns is highly variable and in some cases may be large, while in others it may be relatively small.

Considering the first illustration presented, the saving in peak capacity arising from a combination of the plants might not cover the additional generating plant necessary to supply a reasonable maximum transmission loss. This, however, would be influenced by the number of power plants operated in the unified system, and their locations, as well as by the design of the transmission circuits.

In the case of the illustration of plants (2) and (3) and assuming that plant (2) is to be enlarged to supply both communities, with an accompanying abandonment of plant (3), there is then a saving in peak capacity of 51 kw. After allowing for the added generating plant required for the maximum loss in the transmission line to the smaller community, the saving in cost of equipment afforded by the diversity factor when making the enlargement of plant (2) amounts to between \$5,000 and \$7,500, which could be applied toward providing the transmission circuit. The power required for the small system could be generated at a low figure since about 50 per cent of its load would go to improve the load factor of the unified system without increasing the maximum load.

Referring to the last illustration mentioned above, there would be a saving in plant capacity on account of diversity factor of over 1800 kw., which, expressed in terms of investment, would amount to, say, \$250,000. This can be considered as off-setting plant made necessary by a transmission system, since plant released from peak load service in a growing system stands in lieu of additions to capacity to take care of new business.

Improved Load Factor

Improved load factor accompanies increased diversity factor since increase of the latter decreases the peak load without changing the average load. Referring to the next to the last illustration of diversity factor heretofore given, the weighted average of the annual load factors of the several towns may be taken as 22 per cent. Since the diversity factor between the towns is 1.10 the load factor for all of the towns served together will be 24.2 per cent, while if the diversity factor had been 1.18 as is the case in the succeeding example, the load factor would become 26 per cent. Thus for unified electric systems there is

a saving in operating cost per kilowatt-hour owing to improved load factor as well as on account of the improved operating economies of larger generating plants.

The reduction of labor costs and the economy in consumption of fuel and supplies per unit of output for well considered large plants compared with small plants, is sufficiently recognized to make it unnecessary to consider instances here.

Relative Investment per Kilowatt of Capacity in Larger Compared with Smaller Generating Stations

The installation costs per kilowatt of electric generating plants are dependent upon so many variables, such as accessibility of location, character of foundations required, cost of land, quality of plant, labor saving devices installed, and efficiency, that it is not practicable to show specific relations between costs for larger plants as compared with smaller, but it is undoubtedly safe to say, in general, that the first cost of plant shows an advantage in favor of larger stations. In considering the investment in generating plants associated with unified electric systems, a disturbing factor enters in the form of power plants that must be discarded when local central station systems become absorbed in consolidated systems. But commonly such plants are absorbed into the more comprehensive systems on account of their inability to provide adequate service at low cost, so that the transmission companies often have sufficient leeway in the matter of rates to enable them to care for plant abandoned on these grounds.

The development of steam turbine generating units has an important bearing upon this matter. Some of the larger turbine stations have been built for less than $90 per kilowatt of rated output including all buildings, equipment and lands; and a detailed estimate for a very large plant has recently indicated that the total investment may go below $70 per kilowatt of rated capacity when suitable and well-located land of relatively low price is available for the station. These figures are to be compared with the usual costs of the older types of stations which have been from $110 to $170 per kilowatt of rated capacity. These improvements have come about with the advent of the steam turbo-generating unit as a commercial machine, but other forces have also played a part in the result.

Spare Equipment

In general, as generating plants increase in size, or as two or more are brought into parallel operation, the percentage of

spare capacity required to provide thoroughly reliable operation decreases, since one spare unit having a capacity equal to that which is eliminated by the disabling of any one of the generating units is sufficient either for one plant or for a combination of plants of ordinary capacities.

General Management and other General Costs

The aggregates of salaries of officers, other general salaries including directors' allowances, and general office expenses for all of the electric companies of the Commonwealth of Massachusetts, as shown by the 1909 report of the Board of Gas and Electric Light Commissioners, are as follows:—

Salaries of officers	$234,853.03
Other general salaries, including directors' allowances	496,772.81
General Office expenses	307,443.54
	$1,039,069.38

In the general office expenses are included advertising, canvassing and engineering expenses.

The total expenses of operation, including taxes, legal expenses, insurance, bad debts, etc., for these companies aggregate, $6,279,046.26.

These figures show an average ratio of management expenses to total operating expenses for the electric companies in the Commonwealth of Massachusetts amounting to 16.5 per cent.

The ratio for larger electric companies may in some cases be less than for smaller companies, but in general the ratio seems to tend toward an increase as the companies become larger and more comprehensive. This is not surprising, since when companies reach large proportions it is possible for them to obtain the benefit of the services of technical and commercial men of the broadest and highest ability as their general officers, and to have a trained specialist at the head of each of their important departments. Thus a most efficient organization is obtained, composed of very capable men each having a single primary function in the organization as against the necessity existing in smaller companies of having one man directly responsible for many or all of the functions of the organization. By having such effective supervision of each department, the larger companies are enabled to make material savings by elimination of mistakes in general policies and in construction

costs, and through taking advantage of all possibilities for reduction in operating costs by use of the most economical methods.

Possibility of Providing Rural and Suburban Service

I have included as one of the advantages obtained by consolidated and unified electric systems covering large territories, the ability to provide rural and suburban service that could not be profitably developed by local central stations. How large a factor this may become is difficult to predict, but that it is well worth careful consideration can not be doubted. While such service will provide valuable load, it will also place a company in position to give more comprehensive service, which should raise its standing in the estimation of the public.

When electric companies were originally organized, the product they had for sale was a luxury, consequently they were under little or no obligation to the general public. But electric lighting and power quickly became indispensable, and to-day if electric supply were discontinued it would seriously affect both the business and the recreations of all civilized countries. On this account, economists argue, responsibility now rests upon those providing electric service to manage their properties so that they will sustain an appropriate part in the affairs of business and recreation as well as earn satisfactory returns for the security holders. This involves the planning and operating of electric plants so that they may economically serve all who will be benefitted; and if the argument of economists is finally sustained by the judicial sense of the people, these plants will come into relations similar to those of common carriers, and must then serve all comers within reach,. whether urban or rural.

Service that is too Extensive for small Companies

The immediately foregoing factor is closely related to this one. The electric lighting and power business in territories served by small central stations is seldom fully developed. This condition frequently enables a transmission company to enter a district with the certainty that a paying additional development can be made even though the existing service alone might not justify the extension.

Regardless of how small the fixed population of a community may be, an extended electric system which enters the territory is in position to provide service to consumers whether large or small. There are many instances where large power users are

far from being practicable customers of small central stations, but which may be quite satisfactory customers of a comprehensive system. Some of these are purely summer users, such as stone quarries, stone crushing plants, and pumping plants for irrigation purposes; while in many cases mills and factories, whose power requirements are too great to be economically and reliably served from a local central station of ordinary capacity, may be admirably and profitably served by comprehensive transmission systems. It is likely that rural service will prove to be largely an off peak load since the power demand of an ordinary farm usually ceases at dusk.

A large company is usually in better position to obtain funds for large extensions than a small one, which gives it an advantage in being able to make additions to its system which would be impossible for the smaller company, and thereby to obtain business which is not within reach of the latter although it may be desirable for the community and profitable to the comprehensive company.

Probably one of the most important advantages which a strong, unified and comprehensive electric system possesses over a number of small separate supply companies serving a territory, lies in its ability to serve consumers profitably which the smaller companies are unable to serve. The advantages of the company with extended power lines are emphasized through the improvement of load factor which may be accomplished when the requirements of several cities affording good winter loads are associated with the power loads of industries which operate only in the summer.

The foregoing illustrations and arguments show that there are many elements tending to make the serving of large territories from unified electric systems an economic advantage; but it should be clearly borne in mind that success of such systems must depend upon making the advantages obtained offset the losses occasioned by the transmission circuits and apparatus, the cost of their upkeep, and the appropriate charges to depreciation and for extraordinary costs, together with a reasonable return on the added investment involved.

An illustration of what may be accomplished by a comprehensive electric system supported by good engineering skill is found in the case of an eastern municipality comprising a scattered population of about 30,000 inhabitants which was served by a local central station. This town became a unit in

the distribution system of a large unified steam-electric system, by purchase of the local plant, and a careful estimate showed that the aggregate sum that the customers would pay per year, under the new conditions for service of equal amount and quality, would be about 18 per cent less than under rates required to net the purely local company a fair return on its investment after taking care of legitimate costs of operation. The service under the new conditions is manifestly of profit to the present supply company.

DISCUSSION ON "THE ADVANTAGE OF UNIFIED ELECTRIC SYSTEMS COVERING LARGE TERRITORIES." NEW YORK, FEBRUARY 10, 1911.

P. Junkersfeld: The author of the paper has summarized and pointed out many of the advantages of unified electric systems as compared to electric service by a considerable number of independent undertakings all in the same general territory. These advantages can undoubtedly all be realized to a greater or lesser extent. However, the ultimate success or failure of any such unified electric power system depends in very large measure upon four things:

1. The general character of the territory.
2. The cost of fuel and in some cases the availability of water power.
3. The conception, financing and design of such power system.
4. The management and development of the business.

In analyzing the character of the territory, we should consider such points as size and nearness to each other of towns and villages; growing or apparently stationary population and character of population; nearness to or isolation from some large city or metropolitan or industrial district and growth of such city or district; existing and prospective transportation facilities; tendency toward summer houses, summer resorts, amusement parks and interurban travel in any part of the territory; if the territory is agricultural, is there a tendency toward enlargement, or subdivision of farms, toward raising or fattening live stock, dairy farming or truck gardening. All of the above and other points that might be mentioned under this general heading have a material influence on the amount and combined load factor of the electricity that may be used for all purposes, and the economy with which it can be distributed.

The cost of fuel has a direct influence on the area that can be economically served by a unified electric system, and which is illustrated in several of the systems mentioned by the author in his paper. The plants serving individual or even two or three adjacent towns or villages are of necessity in most cases non-condensing steam plants, while unified systems are or would in most cases be served by condensing steam plants, and in some cases by water power or a combination of the two. The greater the cost of fuel, the greater the margin between cost of production in condensing and non-condensing plants, and hence the larger amount of investment in transmission conversion and distribution that would be justified. This in turn means a larger amount of business for the unified system and because of the increased quantity, better load factor and better diversity factor, a lower cost of production. The load factor and diversity depend upon the similarity of towns.

A high cost of fuel also means a greater probability that all industrial and commercial establishments will purchase the elec-

tricity they need from the unified system instead of some of them attempting to generate electricity in isolated plants on their own premises. This again makes for lower cost of production in the unified system. After an analysis of any given situation as to general character of territory and cost of fuel, if found to be favorable, it then becomes a question of experienced business and engineering judgment as to whether the time has come for a unified electric system and if so, how extensive it should be at the start, and for several years afterward. In arriving at such a decision, local conditions must obviously be taken into account, and also in many cases the market condition for the sale of securities. In this respect the unified system has a very great advantage over the small individual undertaking as was so well pointed out by such an eminent authority as Mr. F. A. Vanderlip, President of the National City Bank of New York, in his address of June, 1909, before the Atlantic City Convention of the National Electric Light Association.

The design, construction and extension of a unified electric system and the molding into such a system of many dissimilar local plants and systems, presents many problems requiring skill and experience. The generation transmission and conversion problems are most conspicuous, especially at the beginning of such an enterprise, and hence usually receive most attention. The necessity for equally careful attention to matters of distribution, and service to customers within individual towns or among adjacent towns or villages is very often not so well appreciated. If great care is not taken, the losses due to unproductive investment or inefficient arrangement, will be surprisingly large. This distribution engineering work not only at the start but continuously during the subsequent development and operation requires consistent good judgment and conscientious effort from day to day as a successful enterprise should keep on growing with the increase in population.

A unified electric system needs and can afford more skillful and experienced management than an individual plant.

In building up new business and in extending the service lines simultaneous experience in several different communities accumulates and which if taken full advantage of, means more rapid progress. In engineering, purchasing, construction and operation of the physical property, the advantages are beyond question.

The one thing most to be guarded against is the so-called "getting out of touch" with the various individual communities; in other words, not giving personal and prompt attention to requests and complaints and personal interest in and attention to the ambitions of the various localities. This, however, is largely a matter of getting and retaining a properly qualified representative for each locality. Moreover, this difficulty is not confined alone to unified electric systems.

There is one very great advantage in unified systems that

was touched upon by the author, but which deserves further emphasis, namely the stability of the investment. It is the old story "in union there is strength". A single town may prosper and flourish for a time and then suddenly recede and in some cases finally become almost depopulated. The investment in the electric plant has become practically worthless. Several such contingencies to a greater or lesser extent have occurred in different parts of this country. A multitude of towns and villages are not likely to all stop growing, much less to decrease in population. A decrease in population in one or more usually means a greater increase in the others, and the net result in the entire group in almost every part of this country is an increase in population and hence an increase in business.

Stability of investment or lesser risk means lower rate of interest. This means greater borrowing power and ability to get sufficient money for construction as substantial as the ultimate economy may indicate to be necessary and also for such extension to the system as the savings in operation or the income from the prospective new business may justify. As the fixed charges on the investment are the largest items in the yearly expenses it is especially important to have reasonably permanent construction and lowest total rate of interest.

The large majority of plants in small towns afford only a limited service, hence, do not fully develop their respective fields and very many end in a loss to the owner. There is abundant experience to indicate that unified systems with 24-hour service to all townspeople who desire it, and even to some farms located within reach of lines when properly developed and managed in territory which justifies such a unified system, results in better service and lower rates and greatly promotes the use of electricity and electrical supplies. In other words, unified electric systems in the present state of the art and under the favorable condition existing in many localities, are one of the economic necessities of the present day.

W. L. Robb: The thing that strikes me most in this paper is that most of the unified electric systems referred to are connected with hydroelectric developments; and a moment's consideration will show clearly why this is the case.

In the first place, there are relatively few strategic locations for hydroelectric development, and those strategic locations are fixed by nature. One can only locate such a development in a given locality. Another limitation we have in such work is that when we make such a development many of the parts of the system must be completely developed at the outset in order to make an economical installation. That means that the hydroelectric developments in the initial years of their operation, have a large amount of surplus power which absolutely goes to waste, and which cannot be conserved, and we can treat it entirely as a by-product proposition, and can afford, taking the entire system into consideration, to go into territories where a steam plant could never think of entering.

When we consider unified plants operated from central steam plants—there are many strategic locations to choose between—and we can also frequently make new strategic locations by building a small amount of railway. Furthermore, the extent of territory we can serve advantageously from a central system depends on the concentration of the population. A station 10,000 kilowatts capacity could operate much more economical than one of 500 kilowatts capacity; but when we compare a 10,000-kw. station with a 20,000-kw. station, we will find very little difference in the cost. Consequently, with concentrated population, we would not extend to the same distance that we do where there is less concentration.

I believe every public service corporation should supply everyone who wants the service if it can be done without a loss. Unified systems permit public service corporations to go into territories which could never be supplied by small stations. I think the small cities and towns should be considered under two heads—one of the heads being cities of 10,000 to 30,000 or 40,000 inhabitants, where we can operate a central station and earn dividends on the investment; and smaller towns, under 10,000 inhabitants, where it would be absolutely impossible to maintain a public service corporation and give a proper return on the investment.

When there is a unified system with a central station supplying a number of different towns and small cities, the small city gains a great advantage. It gets a better supply of electrical energy; it gets it during more hours of the day, and at lower cost to the consumer, with a given profit on the investment.

The small towns which could not support a public service corporation, can be supplied from such a station, and given good service at reasonable cost to the consumer. This benefits the town in two ways. If it is a residential town, it makes it more desirable to live in it, because we can get electric light in our homes. If it is a small manufacturing town, it makes it more desirable for the small manufacturer can buy power at the same rate as his competitor in larger towns.

I have studied the records of one of the companies in New England which began to spread out ten years ago. It is in a city with a population of 100,000 inhabitants, and during ten years that company has grown until it supplies electrical energy to ten smaller suburban towns, and all that is sold by two public service corporations in neighboring cities, and two municipalities. It has extende ten to twenty miles in each direction. A careful study of the accounts shows that the taking on of the business of these small towns has not materially affected the gross receipts of the company per capita in the territory served, nor has it materially affected the percentage of the gross receipts which are turned over as profits to the stockholders.

F. Darlington: There is one phase of this question that was very ably presented by Mr. Jackson a few months ago in Chicago,

and although it is of great importance here, Mr. Jackson, from lack of space or from undue modesty, has not brought it forward to-night. I feel that it has a large bearing on unification of power plants. Mr. Jackson's Chicago paper was a discussion of " reserve funds, depreciation and obsolescence ".

It is the latter of these, namely, obsolescence, that has important bearing on the unification of power plants and it comes about in this way. We all know that electric companies that were started fifteen or more years ago, whether they were for lighting or for railroad or whatever purposes, have found a large part of the cost of conducting their business has been due to failure of apparatus to meet growing demands. It has not been that electric apparatus is generally worn out, but it has become obsolete, because new demands from year to year require larger and improved machinery. Electrical plants which were good when electric lighting first started were not good when business greatly increased in volume requiring larger generating plants and larger units of machinery. Then again, the electric lighting business was combined with larger electric power service, and this again, in many instances with electric railroading. The result in the past has been that the electric stations of fifteen or more years ago became obsolete because they could not do their work, and not because they were worn out, and so it is to-day with the electric plants of our smaller towns and villages, they are not worn out, but they are being replaced. They are becoming obsolete because large central power plants can do their work more cheaply.

How do centralized power plants meet these changing conditions? They are built for larger service and on a unit plan that can be economically extended to meet growing demands. It makes little difference to their operations whether a village is using electric light or mill power or interurban trolley power, as all a central plant has to do for additional service is to increase the size of its central station, that is to add generating units as required.

One gentleman this evening spoke of the desirability of getting the securities of electric properties so that they will be safe and pay a good return. The way to do this is to spend the money for plants which will be applicable to any condition that may arise, and we may confidently expect that in the future, as it has been in the past, the changing conditions will be toward larger plants and greater powers.

There is one other feature of to-night's paper of which I would like to speak, that is, the question of utilizing off-peak and secondary power. You all know what is meant by these terms. The off-peak power is what we might call the by-product of a central station, and Mr. Jackson has shown that if we take three or four or five or more villages and combine their service on one central station, the combined peak will be less than the sum of the individual peaks, but the combination will accom-

plish more than that. When we combine a number of services on one large plant we combine the off-peak capacities. If we have ten small separate power plants, each of these will have an off-peak capacity when the lighting or railroad or other work on each plant is not at its maximum demand, and this would result in a number of small supplies of off-peak or surplus power, and the separate utilization of the surplus power for each of the ten small stations would be difficult. Now, if you combine these ten stations into one large station, you will have one large supply of surplus power, and the problem of profitably using this is much more promising than it would be were it divided into ten small divisions, and this problem of utilizing off-peak power is finding its solution. Unfortunately, the time has not yet arrived when there is an unlimited market for such power, that is, power which is only available throughout certain hours of the day or night, or during certain weeks or months of the year, but it is a field in which there is excellent prospects of largely extending electrical applications.

There are several very promising methods in view for utilizing off-peak and secondary power. One is for electrochemical uses, and the most hopeful of these is the fixation of atmospheric nitrogen. This is an operation that can be shut down or turned on to accommodate other demands on the power plant, and when it is once established on an economical basis, it will afford a very wide field of profitable use for second class or off-peak power.

Another use that has not been generally made of off-peak power, but which undoubtedly will be greatly extended in the future is irrigation pumping, that is, the use of electrical power for lifting water for irrigating land. One or two electric plants have been put in in the West, almost exclusively for this work, and it has been found profitable, even where the cost of fuel is high, and where the power plants are costly, and pumping for irrigation should be very highly profitable where the off-peak or second class power of large central stations can be utilized. It is a kind of work that can be readily adapted to off-peak hours of operation. Wherever irrigation is carried out two methods suggest themselves. The first is by gravity, which is not always practical, and the second is by pumping and a few figures will show that a small amount of electric power will pump a vast amount of water. Allowing for all the losses in transmission and transformers, in electric motors and centrifugal pumps one kilowatt hour at the power house will lift one and one half acre-feet of water six and one-third feet in twenty four hours. This seems like a small amount of current for a large amount of work, but it is a figure that can be realized, and is based on a net efficiency of 40 per cent between the electrical output of the power house and the potential energy of the water delivered, and this has been realized by actual operations.

Now this means that if you are working in a country requiring one and one-half feet depth of water per year to irrigate

land, 150 kw-hr. at the power house will lift enough water 40 ft. to irrigate one acre. Of course, 300 kw-hr. would lift the same amount of water 80 ft., and this means that if the electric power was charged for at one cent per kilowatt hour at the power house, or about 1.2 cents per kilowatt hour at the electric motor, the cost of electric power for irrigation would be only about $1.50 per acre per year, where the lift is 40 ft., and $3.00 per acre per year where the lift is 80 ft.

There is another possible use of electric off-peak power which has been indicated by very significant experiments in agriculture which seem to show that an electrostatic potential kept up on wires that are strung over land where growing crops are produced, stimulates vegetation and increases production. If this is once established and proved profitable, it means another tremendous field for electricity in agricultural districts and a convenient use for off-peak power.

To summarize briefly the foregoing; the unification of power plants and the building up of large central stations will enable electric properties to meet the growing demands of the future with greatly reduced losses due to obsolescence of machinery. The reduction of obsolescence will go far towards improving the securities invested in electrical enterprises, and increasing the earnings on the investment.

George H. Lukes: The author of the paper has analyzed very fully the several factors which often make it possible to substitute for disconnected systems, supplied from small local central stations, a unified transmission and distribution system supplied from a small number of relatively large central stations.

The success of such enterprises depends largely upon the character of the territory served. If the territory is of such a character as to render possible a considerable expansion of the business, either through rapidly increasing population or the development of power business, then the chances for the financial success of the enterprises are greatly increased. If, on the contrary, the territory is stationary in population, with no prospect for power business, the increase in fixed charges, (due to the large investment in transmission lines and substations) in some cases offsets any possible economies in operation. Our experience, however, shows that when a region is covered with a comprehensive distribution system, opportunities for increasing both power and lighting business often present themselves in territories which, at first sight, seemed barren. In other words, the presence of a supply often seems to create demand. As soon as it becomes generally known that power service can be obtained at a reasonable cost, little enterprises spring up here and there which apparently would not otherwise have come into existence.

Before taking up in detail some of the factors summarized on the first two pages of the paper, it might be well to refer to a very important point in connection with the management of district electricity supply companies, touched on in the third paragraph

of the paper. The advantages of a centralized management are obvious. When, however, the system covers a considerable area and supplies service to a multitude of small cities and villages, it becomes more and more difficult to maintain that close relationship with municipal governing bodies and individual customers which contributes so much towards the financial success of the company. In order to overcome this difficulty it often seems advisable to have an organization which is neither purely functional nor district, but a combination of the two. In such an organization the local manager, or superintendent, is invested with considerable authority along certain lines, so that he can take immediate action to remedy undesirable conditions. Certain parts of the work, therefore, which might be performed more efficiently in the central office, are often delegated to the district offices, and this tends to offset somewhat the possible economies which might be obtained by centralized management.

The author finds after investigation that the diversity factor as between towns is highly variable and in some cases may be large while in others it may be relatively small. This is confirmed by our own experience. In many cases, however, it has been found that when a district supply scheme is substituted for disconnected distribution systems, the diversity factor increases, due to expansion of power business. This is particularly true in the case of the sale of electricity to electric railroads, which class of business is impracticable for small companies, but quite feasible in the case of larger companies.

In the consideration of the reduction in power generating cost due to larger plants and improved load factor, the author seems to have devoted most of his attention to the reduction in cost due to improved load factor. As a matter of fact, a reduction in generating cost often accompanies an increased output regardless of load factor; that is, in the same plant by increasing the output, at the expense of a decreased load factor, it is often possible to effect a considerable reduction in power generating costs.

Our experience confirms the author's statement regarding the possibility of providing rural and suburban service that could not be profitably developed by local central stations. In the case of one company supplying sixty towns and villages, careful examination has shown that not more than forty of these towns could afford to operate independent central stations with success. In other words, the consolidation of a number of small companies into a unified system has resulted in the extension of service to at least twenty, and probably thirty, towns which would otherwise be without the advantages of electric service. Referring to the question of 24-hour service which is invariably furnished by the district electricity supply system, it is very rarely possible for the small local central stations to furnish service more than from dusk to midnight, or at most from dusk to daylight. The furnishing of 24-hour service from a small local station would in-

variably make necessary a much larger investment and greatly increased maintenance and operating expenses. This condition in itself prohibits the supply of electricity for power purposes from the smaller local central stations. In the case of the sixty towns above referred to only one was giving 24-hour service prior to being absorbed by the district electricity supply company.

The question of whether or not district electricity supply companies, deriving their power from steam generating stations, can economically supply purely farming business is somewhat unsettled. The experience of the interurban railroad companies in supplying electric power to farms from their trolley lines seems to indicate that considerable business of this kind may be obtained. It is evident that many farming operations, such as pumping water, grinding feed, etc., might be easily performed by electric motors.

Many people are of the opinion that in the course of time the electric motor will largely supersede the gas engine in general use on farms within the territory of the district supplying systems. It is a question whether the general use of electricity on the farm will not be a strong factor in making farm life more attractive, and thus perhaps have a tendency to hold back the movement of population from the farms to the cities. These considerations lead up to the question of whether the time is not rapidly approaching when, as the author states, it will be the duty of the company supplying a given territory to furnish service not only to the cities, but to the rural communities. It naturally follows that if such is the case these district supply companies must be made in a measure independent of local municipalities, so that one part of a given territory cannot drive a hard bargain with the company at the expense of more remote and weaker communities.

Norman T. Wilcox: The whole trend of modern development is toward centralization and unification of effort; this because there are manifest advantages resulting both to the public and the people who furnish the funds for these enterprises.

If the work is well engineered, so as to increase efficiencies, reduce costs and give fuller and better service, and that of maximum efficiency, the enterprise is likely to be satisfactory; but, on the other hand, if the engineering is in the hands of inexperienced or otherwise incompetent engineers, the results may easily be disastrous and a disappointment to all concerned. It seems to me that the right kind of engineering is essential, even more essential than good management; because if the management is inefficient, we can often get rid of it at slight expense. On the other hand, bad engineering once fastened upon an enterprise is a permanent tax which once incurred cannot be avoided in the future.

In practically all of these unified enterprises, owing to the scope

and complexity of the problems, the right kind of engineering is essential and should not be overlooked.

Philip Torchio: In the birds eye view the author gives of the existing conditions of electricity supply throughout the country and the analysis of the factors that are prompting these developments, we gather a true insight of coming events. This paper shows that centralization of power supply is economically advantageous to the welfare of large centers of population as well as to the most scattered districts. The analytical presentation of the eight reasons for this policy given in the paper brings out two fundamental facts; first, that multiplicity of small stations with unrelated management engender economical losses; and second, that such losses can be retrieved by concentration of power stations and concentration of management. It is the old saying, quoted by Mr. Junkersfeld, " in unity there is strength " to which should be added " in co-operation there is achievement ".

With these fundamental facts well established, there should be no hesitancy in the mind of all fair-minded people, be they engineers, financial men, public officials or private individuals, in lending their support to the advancement of the greater central station. Speaking as an engineer to electrical engineers either engaged in manufacturing or other pursuits, I will emphasize the fact that better opportunities and more business would be laid at our doors by the broad business policies of large central station managements than by the dwarfed developments of a multiplicity of small and unrelated systems.

If the time permitted it would be interesting to supplement the data given in the paper by detailed figures of the results obtained in specific instances by the policy of concentration. As a remarkable illustration I will only make comparison of the operation of the New York Edison Company supplying power to the Manhattan and Bronx Boroughs of Greater New York, and the operation of the London municipal and private undertakings, for the year 1909. The New York Edison Company had a total plant capacity of 173,100 kw. with a maximum load of 139,667 kw., all of the maximum load being generated at two main stations operated in parallel. The city of London with thirteen municipal undertakings and fourteen private companies, had a total plant capacity of 235,049 kw., and the sum of the yearly maxima of all the undertakings was 141,148 kw. From this comparison we see that the New York Edison Company had in 1909, 24 per cent spare capacity, while the City of London had 66 per cent spare capacity, which figure does not take account of the diversity factor of the twenty-seven different undertakings, which diversity factor would certainly have considerably reduced the contemporaneous maximum, thereby making the spare capacity still greater than 66 per cent.

I would like to say considerably more on the possible economies of unified systems operating in the same or contiguous

territories, but the subject is too broad and the discussion would lead us away from the subject of this paper covering large territories. I think, however, that in Mr. Jackson's presentation of the hydraulic developments of electric transmission systems serving large territories, which illustration could be still more emphasized by developments in foreign countries, he has touched upon the essential truth that with cheap cost of power generation the central station can reach any market, almost regardless of distances. This refinement in production cost alone would influence directly only to a small degree the ultimate cost of power to the consumer in one locality, but it will indirectly enable the central station to extend its radius of activity, and by the general economies made possible by such unification of scattered districts the whole community will reap material advantages from such unifications.

The proper methods for the realization of these operating and investment economies are gradually becoming more and more recognized, principally through the efforts of a few men who have had the courage of their convictions and have ventured their capital in pioneering the development of the greater central station. While many obstacles are still in the way of the aims of these men, I do not think that the people of this country will overlook the great national economic benefits of this activity. It is only a few years ago that I gave utterance to a forecast of the future development of central stations, which forecast was at that time characterized as a poetic utterance, but now after listening to Mr. Jackson's paper and this discussion, it does not seem so nebulous and far from ultimate realization. I quote these remarks as follows:

"In closing this forecast, I would say that in the progress of the gradual uplifting of the industrial efficiency of the country, it is the province of the central station companies to furnish to the nation all of the power required by it in all commercial, industrial and agricultural needs. With thousands of central stations dotting the map of the United States, with a closely woven network of power wires connecting the heaviest centers to the most humble hamlets, is it not reasonable to expect that this wonderful organization should ultimately command and control within this territory the generation and distribution of power for everything that lights or heats, or operates machinery, or propels vehicles or trains?"

L. L. Elden: The author of the paper presented this evening has brought to our attention the favorable results of the unification of electric systems into larger organizations. In citing examples of successful combinations, reference has been made to the Boston Edison system with which I am connected. In confirmation of the author's conclusions as to the favorable results attained by the combined companies due to the diversity factor, I submit an analysis of the actual result in the Boston system based on the operation of the system in 1910. The sys-

tem supplies 35 cities and towns by means of two generating and 28 substations. Considering the peak-day of 1910 in December and excluding transmission and conversion losses the ratio of the sum of the individual district peaks to their coincident peaks shows a diversity factor of 1.03 or as 38,000 to 37,000 kw. Considering the whole year's operation, this ratio is changed to 1.08 or as 40,000 to 37,000 kw. in favor of the combined system in each case.

The total losses in the transmission system and converting apparatus at the moment of the system peak aggregated 11,000 kw. equal to 23 per cent of the total generated kilowatts. Assuming the cost of the generating system at $125 per kilowatt, the total saving due to diversity factor is $125,000 while the increased investment necessary on account of losses is 11,000 kw., equal to $1,375,000, or a net increase of $1,250,000. This difference in investment must be included in capital account upon which dividends or other charges must be earned, a result which can only be obtained by an increased load factor on the generating station, more economical management of the combined system and the exercise of the highest executive and engineering ability as embodied in the controlling organization. One of the most serious problems before the larger company is the disposal of the discontinued generating equipment of the smaller companies in a manner which will not impair the financial interest of the controlling company, this apparatus usually standing on the books for original values, only a small fraction of which can be obtained when sold. Owing to these conditions, it is sometimes true that the generating apparatus maintained after consolidation is sometimes in excess of the capacity of that previously maintained by the several companies. This may be due to the introduction of larger and more economical units, and to the reluctance of the management to abandon perfectly good and modern apparatus which may be of value in emergencies or during peak loads. As an example of improvement in load factor on the main generating station due to the absorption of several companies into our system, an increase of 5 per cent was noted by an addition of business aggregating a kilowatt demand, approximately 1/15 of that previously observed.

The most important result of consolidation is the ability to serve large interests with practically unlimited amounts of power at rates and under conditions prohibitive in the smaller companies, due to lack of suitable apparatus and the inability to manufacture energy at less cost than the prospective consumer, conditions which are completely altered in the case of the combined companies.

Charles P. Steinmetz: I do not believe that there is a limit to the economical size of an electric generating system. While this opinion has frequently been expressed, and the economical limit placed at 10,000 or 20,000 kw. or even higher, yet the experience of recent years seems to contradict this, and to show that

even with systems of 100,000 kw. capacity, an increase of the system leads to further economies. The 20,000 kw. units are more economical than 10,000 kw. and therefore a system using five, 20,000-kw. generators, is more economical than another using 10,000-kw. units. This means a system of 100,000 to 200,000 kw. total generator capacity, considering the number of units which are required to secure the economical use of units at all times.

There is no doubt in my mind that with an increased demand an increase of the system from several hundred thousand kilowatt to possibly millions of kilowatt will lead to still superior economies, if by no other means, at least by the fact that these very large systems can command the services of engineers which smaller systems cannot command.

Another subject is the utilization of spare power and off-peak power. I am interested in the data given on the power required for irrigation, and the relatively small amount of power it costs to operate a pumping plant for irrigation purposes.

Another use for off-peak power is the fixation of atmospheric nitrogen. We are rapidly approaching a time where we shall have to rely on fertilizers to maintain the productivity of our soil. Now the commercial production of nitrogen compounds by electrical power has been conducted successfully and economically; but only where the development of the water power has been extremely cheap, and where there was no market available for it—as for instance, in Scandinavia.

We must however realize that the main part of the cost of installation of such industrial operations is due to the plant needed to convert the very diluted nitric oxides into nitric acid, or solid nitrates for transportation; therefore a large part of the cost is due to the chemical side of the production.

When we come to intermittent use of the off-peak power, where the plant is used only for a part of the time, then the cost of the production rapidly increases, due to the interest on the investment, and we find, very soon a point is reached where the production of nitrates would not be economical, even if the power cost nothing. Herein consists at present the great difficulty of utilizing electrical power for the fixation of nitrogen. But since this results from the cost of concentration, then if we could use the fixed nitrogen in a highly diluted state, we could save most of the investment, and so materially reduce the cost; and it would be economical. That means that this method of using off-peak power lends itself nicely to the combination with irrigation. We might use electrical power for irrigation, and also for producing nitrates, and send out the nitrates as fertilizer with the irrigating water in a highly diluted state. In this way you could use a large amount of electrical power, and get the benefit of intermittent and off-peak power available in arid districts.

A Member: The author has presented some interesting facts in regard to this subject, and some of the speakers have supple-

mented that with the fact that in this distribution we should have good engineering and consider what territory the company should extend to.

Assuming a company located in a city of 40,000 people surrounded by towns of various sizes, under ordinary circumstances how long can it afford to make its extensions to reach these towns?

Suppose we had a town of 1,500 people? Could we afford to extend three miles to reach such a town, or ten miles, or how many miles? Suppose it was a village of 600 people, could the company extend three or six miles to such villages?

This is a very practical point, and in all of the talk to-night I have not heard a word as to just how far we could go to reach these various towns. I appreciate that it depends on the town itself—that is, whether there is manufacturing there, or what the conditions are; but this question of the cost of transmission lines seems to me a very important factor in this problem; and also, the cost of operating the substation. These questions seem to be more important than the question of what the power costs. But, assuming that additional power can be produced for one-half a cent per kilowatt-hour, how far can these lines be extended? The net work of the towns and the number of them, would of course affect it.

Wm. B. Jackson: There is just one point regarding which I will take a few moments to speak. During the discussion it has been suggested by several that most of the illustrations of unified systems I have presented relate to hydroelectric developments. This is true, and in a way indicates the fact that the number of important unified electric systems using water-generated power is at present much greater than the number of those using steam-generated power. This condition may be largely accounted for by the inherent character of most water-power developments which makes it necessary to have more or less important unified electric systems to make possible their profitable development. But I believe an element of large importance is found in the fact that our plant managers who are operating steam-electric plants have not, as a rule, had the courage or have not had the opportunity, to seriously attack the problem of building comprehensive systems. The facts show that, under suitable conditions, where ever the problem has been attacked with courage and with excellent engineering and commercial organizations, comprehensive steam-electric systems have grown and flourished. And to-day one finds scattered over all parts of the country steam-electric systems that are gradually working into unified systems in addition to those which have already become comprehensive in their scope.

It must therefore be expected that unified electric systems receiving power other than from hydroelectric developments will become relatively more and more numerous and important.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 14, 1911.

HIGH-TENSION TESTING OF INSULATING MATERIALS

BY A. B. HENDRICKS, JR.

INTRODUCTION

Great accuracy in the high tension testing of insulating materials is not yet attainable, due to the variability of the materials, the difficulty of exactly controlling all the conditions of test, and in many cases, to the unreliability of the apparatus and methods employed.

The methods, results and conclusions of different investigators thus vary between wide limits and a close agreement between them is not to be anticipated.

There are exceptions to every statement that can be made regarding insulating materials. Those given herein represent the personal experience and opinions of the writer and are intended to apply to laboratory tests on small samples of commercial insulating materials only.

No attempt will be made to cover more than a few of the salient points, nor those which have already been thoroughly discussed, the latter including the testing of wires and cables, line insulators, and finished apparatus.

Tests. The tests under consideration are those for the determination of

1. Ultimate dielectric strength and arcing voltage.
2. Energy loss or dielectric hysteresis.
3. Specific capacity.

My own experience in the different departments of this field is very unequal, being confined chiefly to tests for dielectric strength and arcing voltage, but it will be of interest to consider also dielectric hysteresis and capacity.

Testing Apparatus

There are four main elements to be considered.

1. Alternating-current generator.
2. High-tension transformer.
3. Controlling apparatus.
4. Measuring apparatus.

Power Required. The results of tests for dielectric strength and arcing voltage will depend to some extent on the power and regulation of generator and transformer, and it may be considered necessary to reproduce exactly the conditions of a large power system in order that laboratory tests may give reliable data on the performance of the material when in actual use. This is hardly possible or desirable and it therefore becomes necessary to determine the requirements which must be fulfilled in order to obtain reliable results with apparatus of limited power.

It is necessary and sufficient that normal wave form and voltage be maintained, up to complete failure of test piece and the formation of a dynamic arc.

The critical, final moments of test are liable to be attended by high-frequency oscillations which sometimes form a complete flash over without leading to a dynamic arc. These oscillations have negligible influence on the voltage of normal frequency. till a flash over or momentary arc occurs, which may be attended by a sudden drop in voltage sufficient to prevent the formation of a continuous arc. It is at this point that the influence of the energy available becomes important, while previously it is of small consequence, the load being extremely small. The best that can be done is to provide apparatus of capacity sufficient to supply the small charging and leakage current and the energy absorbed by dielectric hysteresis, with the closest possible regulation and minimum distortion of wave form. By regulation is meant not only the voltage drop under continuous normal load but particularly the drop at the first instant of short circuit, or the capacity for instantaneous short-circuit current.

It is believed that the influence on results of the power of the testing apparatus has been somewhat exaggerated. For puncture tests (as distinguished from arcing tests) on small test pieces and particularly on oil, and for measurements of dielectric hysteresis and specific capacity, reliable results, comparable to those obtained in actual practice, may be obtained with very

small generators and transformers. These must be well designed and of characteristics especially adapting them to this use.

For all of the tests under consideration the power and current required are usually very small though the power factor may be low. It is, therefore, entirely feasible to provide apparatus of much greater volt ampere capacity than will normally be required, thus insuring close regulation and minimum distortion of wave form.

Generator

Generators of the distributed field type have the essential characteristics and are now available in sizes suitable for laboratory work. These machines of high speed and distributed field and armature windings not only give an almost perfect sine wave at all loads and power factors but deliver very high energy at instant of rupture of the dielectric; that is, they have great capacity for instantaneous short circuit current, due to low armature impedance.

Ordinary revolving-field machines of distributed armature winding but non-distributed field winding, may give a sine wave at no-load but are liable to produce distorted waves with higher harmonics of considerable magnitude under small loads of low power factor, such as is represented by the core loss of transformer and capacity current of test piece, and are thus less suitable for this work. The armature impedance is high, hence the capacity to deliver great energy at instant of short circuit is also limited.

Small Generator. It is evident that a small generator with capacity for maintaining the voltage wave normal for a few cycles at the critical moment of rupture will give results approximating those on a large power system, where considerable impedance intervenes between generator and point of breakdown.

Excellent results may be obtained with smooth-core alternators of the old Thomson-Houston pattern. These are now obsolete but may be obtained at very small cost of the dealers in second hand apparatus.

The wave form of these machines is an almost perfect sine, their chief limitation being poor regulation. Nevertheless they are on the whole very satisfactory and most of the results given herewith were obtained with them.

Examples. A steam turbine generator of the distributed-field type is shown in Fig. 1, and the wave form in Fig. 2. The illustrations and waves represent a 25-cycle, two-pole machine,

but it is believed that at 60 cycles, 4-pole, the wave form would be equally as good. The field winding would then occupy 34 slots, resembling a direct-current armature.

A Thomson-Houston generator is shown in Fig. 3, and the wave form under load, while testing a high-tension transformer terminal at 69,300 volts, is shown in Fig. 4. The transformer used is similar to that shown in Fig. 5, the terminal under test being connected between one terminal of transformer and the grounded neutral point. The oscillograph was connected directly across the 69,300-volt terminals in series with a non-inductive resistance consisting of glass tubes filled with distilled water.

The potential wave shown is in almost perfect agreement with a mathematical sine wave.

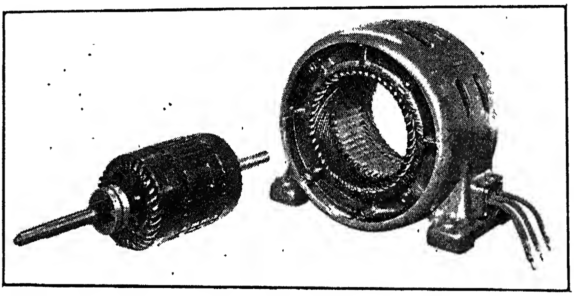


FIG. 1.—Sine-wave generator—distributed field type. 37.5 kw—three-phase—25 cycles

TRANSFORMER

Capacity. There has been a good deal of misapprehension in connection with the question of transformer capacity. It has been usual to specify a certain minimum kilowatt capacity for a given voltage, regardless of the other characteristics of the transformer, not realizing that such a specification is indefinite. The rating of these transformers is more or less arbitrary and elastic, as with a given design but slight changes are necessary in order to halve or double the nominal capacity as stamped on the name plate.

The space occupied by the copper as well as the loss therein, is very small, hence the current rating could easily be changed to this extent, with negligible influence on the rest of the design. It is not the rating stamped on the name plate that determines

the energy in the discharge circuit but the regulation, particularly as expressed by the impedance voltage, which has thus to be taken into account.

In the tests under consideration the conditions are always at one of the extremes of small load or dead short circuit, except for an instant immediately preceding breakdown. Thus the reactance is of chief importance.

In specifying transformer capacity there should then be expressed the kilowatt rating, and the resistance and reactance

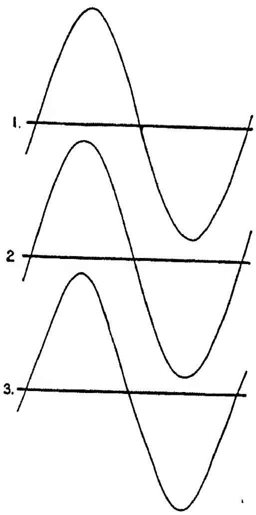


FIG. 2.—Potential waves of generator (Fig. 1). 1. No load. 2. Mathematical sine. 3. Full reactive load on one phase—wave form of loaded phase

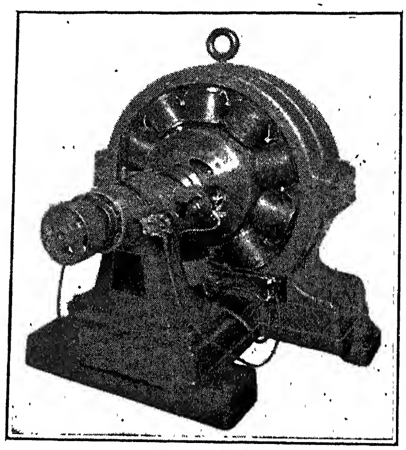


FIG. 3.—Thomson-Houston smooth core alternator—35 kw.—single- phase—125 cycles

voltages at full load, the kilowatt capacity being of interest only as a basis for determining regulation.

Fortunately there is no difficulty in obtaining very high kilowatt capacity with close regulation. The secret of the best designs of high-tension testing transformers lies in the use of extremely massive cores, few turns in the winding, and reinforced insulation of the end turns. By these means the poor regulation of the transformer and the great liability of the end turns to short circuit have been overcome.

Many transformers for this work have been designed simply as

large induction coils with closed magnetic circuits. The small cores employed necessitate a very large number of turns in the high-tension winding, which is objectionable for two reasons; the winding becomes delicate and bulky, and the reactance, being proportional to the square of the number of turns, is very high. It is much better to increase the cross-section of core and the volts per turn, as the core is not liable to break down and the reduced size of winding may be better insulated and in every way made more substantial and reliable. Modern designs therefore operate at 5 to 20 volts per turn instead of 1 to 3 as formerly.

The small number of turns renders the use of large conductors permissible, which is also of advantage from increased mechanical strength and less danger of open circuits.

Thus the transformer should be designed throughout as a *power transformer* and preferably for continuous full-load operation, as contrasted with the usual bulky and delicate constructions of large impedance.

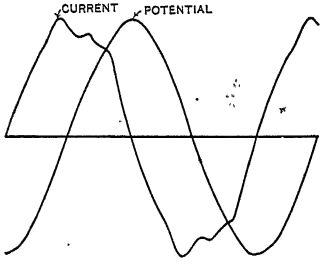


FIG. 4.—Thomson-Houston generator—current and potential waves

Failures. The principal cause of failure of such transformers is from short circuit of the end turns caused by high-frequency oscillations. These may be generated either outside or inside of the transformer, the resultant stress being concentrated on the end turns in either case.

In order to protect the end coils a few turns should be insulated with a very high factor of safety. In a transformer with 20,000 turns in the high-tension winding, it has been found sufficient to insulate 100 turns at each end to withstand 1000 to 2000 times normal voltage between turns, and to provide extra insulation between the end coils and the rest of the series.

In addition, a choke coil without iron core should be connected to each terminal, external to the transformer.

Double Voltage Test. By the standardization rules of the A.I.E.E. testing transformers are required to stand double normal high-tension voltage between high-tension winding and low-tension winding and iron, for one minute.

For all ordinary purposes this is an excessive and unnecessary requirement as it subjects the insulation throughout to four times the maximum strain normally applied to the terminals

only, thus demanding maximum insulation for middle point of winding the same as for the ends, though in practice this point can never be subjected to more than half voltage.

The transformer may be built to stand such strains, but at a great sacrifice in size, cost and operating constants, and nothing of real value is to be gained by such designs.

There is little danger of breakdown to low-tension winding or iron, failure usually being due to short circuit of the end turns by high-frequency oscillations.

A better and more rational method of test is to apply an induced voltage of 50 per cent above normal, the middle or end of high-tension winding being grounded. This in effect applies $2\frac{1}{4}$ times normal strain throughout, and is ample.

It is here assumed that the *strain* is proportional to the *square* of the *stress* or voltage.

Time Rating; Cooling. In addition there should be a time rating. Such transformers seldom operate for more than a few hours at a time. For the lower voltages, where the losses are small and radiating surface of tank ample, there may be no necessity for limiting the time of continuous operation, especially as the usual designs are extremely large for the capacity, compared with ordinary power transformers.

The case is different when voltage is high and the design more compact. There is then insufficient radiating surface for continuous operation (more than ten hours) and artificial cooling must be resorted to. It has also been found that the heating effect of the loss in the insulation must be taken into account. Negligible at low temperatures, as for one hour operation, this loss may equal the core loss after ten hours run, increasing very rapidly with the temperature, accompanied by a great decrease in the dielectric strength of the insulation, and consequent danger of breakdown.

Thus it becomes of the highest importance to keep the temperature as low as possible, much lower than for ordinary designs, as thereby the problem of insulation is much simplified.

By using a more bulky design, providing great radiating surface, and a higher factor of safety in the insulation, the necessity for limiting the time of operation, and for artificial cooling, may be eliminated. As result therefrom, the size, weight, cost, core loss, and impedance will be greatly increased.

Grounded Neutral. A great gain may be effected by normal operation with middle point of high-tension winding permanently

grounded. For the majority of laboratory tests there is no good reason why this connection should not be used. Thereby the stress is reduced one-half and the major insulation about three-fourths at one stroke, resulting in greatly reduced size of transformer and much better electrical constants throughout. Grounding is also necessary in order to make use of voltmeter, ammeter and wattmeter at center of high tension winding as described under "Measurements."

The ground connection may be made so as to be readily broken without dismantling the transformer, so that tests may be made with either terminal grounded or free if necessary.

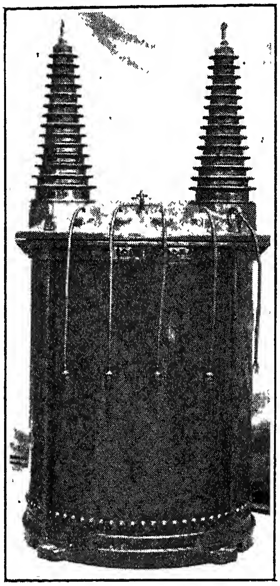


FIG. 5.—100-kw., 200,000-volt testing transformer—with grounded neutral

The advantages of the grounded neutral are very great as it results in a radical reduction of size, and improvement in efficiency and regulation.

One of the transformers used in the present investigations is shown in Figs. 5 to 7 and has the following characteristics.

100 kw., 60 cycles, 2000 to 200,000 volts

Volts per turn	10
Impedance voltage	7 per cent
Resistance voltage	1 per cent
Regulation—unity power factor	1.25 per cent
Tank—height	52 in.
Tank—diameter	44 in.

Neutral point of high tension winding is grounded.

Figs. 8 to 10 represent a standard type of high-tension transformer of large capacity designed for factory tests of line insulators. In this also the neutral point of high-tension winding is grounded.

Controlling Apparatus

The voltage must be varied through a wide range in a perfectly regular manner without breaks or steps. To effect this many different methods are in use, but generator field control is by far the best for laboratory work.

Field Rheostat. This should be designed to vary the generator voltage in a perfectly continuous manner or in very small steps, and the generator should always be operated at excitation as near normal as possible, for the sake of close regulation and good wave form.

Multiple Windings. Either the generator or the low-tension winding of the transformer should be wound with four parallel circuits. These may be connected in all necessary combinations by means of series parallel switches, cylinder controllers, or terminal boards with movable links.

The last named method is inconvenient in use; series parallel switches are simple and satisfactory, but the cylinder controller is least liable to lead to mistakes, and is quickest in action and therefore best.

Four parallel circuits on the low-tension side of the trans-

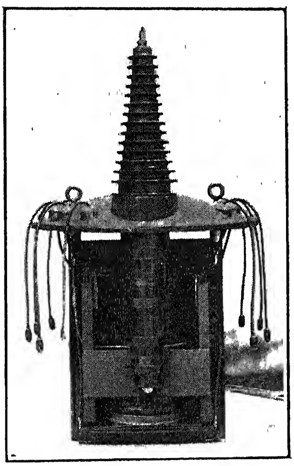


FIG. 6.—100-kw., 200,000-volt testing transformer—interior side view—showing voltmeter coil at center of high tension winding

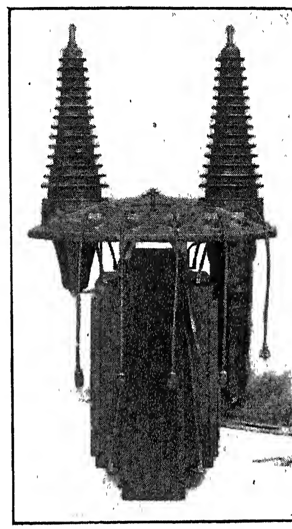


FIG. 7.—100-kw., 200,000-volt testing transformer—interior end view.

former have been found ample, and are more readily provided than on the generator. This gives 25, 50 and 100 per cent transformer voltage at normal generator voltage. The latter may be varied from 50 per cent to normal voltage, thus giving a range of $12\frac{1}{2}$ to 100 per cent transformer voltage. If a greater range is required it should be provided by a suitable transformer.

Taps on High or Low-tension Winding. These should not be used and are unnecessary when four low tension coils are provided.

Taps are always hard to insulate, and if on the high-tension side also necessitate a separate terminal insulator for each tap. Extra insulation of coils adjacent to taps is required, the same as on end coils unless the winding is in two parts with taps near the center not used for terminals. These inside connections are difficult to bring out and properly insulate and their use requires handling of the high-tension circuit. Multiple high-tension windings are objectionable for the same reasons.

Multiple Transformer Units. A number of transformers of

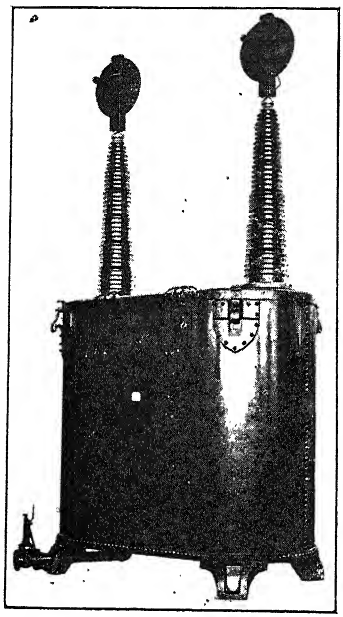


Fig. 8.—250-kw., 400,000-volt testing transformer—with grounded neutral

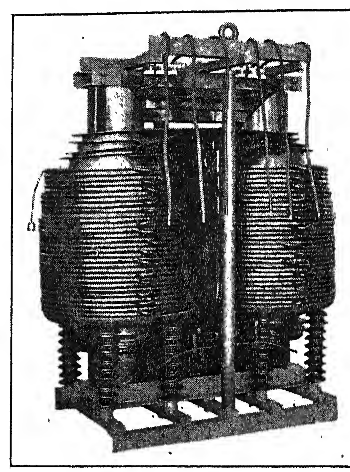


Fig. 9.—250-kw., 400,000-volt testing transformer—interior view

comparatively low voltage may be connected in series to obtain any desired total voltage. As each unit must be insulated to stand the voltage due to its position in the series, nothing is to be gained by this arrangement.

Intermediate insulating transformers may be inserted, but add to the complication and are otherwise disadvantageous.

Since transformers are now available of capacities up to 500,000 volts or more in a single unit, there remains little reason for the use of multiple units, or for more than two at most.

Measuring Apparatus

VOLTAGE MEASUREMENTS

Opinions differ widely as to the best method of determining the voltage of the discharge circuit. As this is by far the most important, and in most cases the only measurement made it should receive the most careful consideration.

Spark Gaps. For certain special measurements this is the only method that can be used. It is however liable to be the source of errors and trouble.

Its use is authorized by the A.I.E.E. standardization rules and therefore, quite commonly insisted on, although in the opinion of many experimenters the device is not as reliable as desirable.

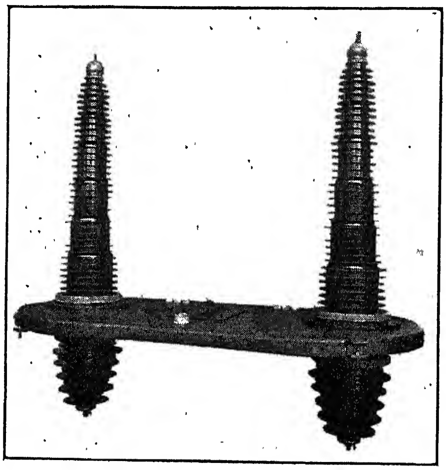


Fig. 10.—250-kw., 400,000-volt testing transformer cover and high-tension terminals

It is my desire to have the A.I.E.E. reopen the question of the proper method of measuring testing voltages, to further investigate the limitations of the spark gap and consider the use of the method I have found most satisfactory, namely the voltmeter coil on transformer core.

It has been stated by Fisher (International Electric Congress, St. Louis, 1904) that the use of large disks back of needle points gives more regular results. My own experience with this arrangement has not been thorough enough to warrant definite conclusions, but it would seem to be, in general, subject to the same criticisms as the plain needle point gap.

It has also been claimed that spherical electrodes are superior

to needles, but there is the added labor of frequent refinishing or replacement of the balls.

Fig. 11 represents the results obtained with needles and ½-in. (12.7 mm.) balls under identical conditions using a sine-wave generator Fig. 3 and a 50,000-volt transformer quite similar to Fig. 5, the spark gap being connected direct to transformer terminals, and the voltage controlled by series parallel switches and field rheostat. The results with needles and with balls seem fairly definite, but it is extremely doubtful whether they would remain constant if any of the conditions were changed.

The spark gap is only an indirect means of determining voltage. It is generally used to find the voltmeter setting for a definite gap when a specified voltage is to be applied to test piece or to measure an unknown voltage by successive trials with different settings.

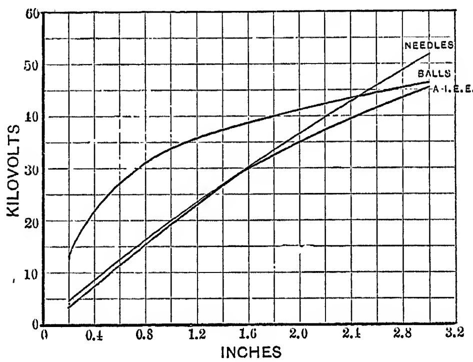


Fig. 11.—Curve of needles and balls

In either case great accuracy is not possible and the method is tedious in application. Errors may be introduced by the fact that conditions may not be the same during the spark gap trials and the actual test, since the test piece and gap may not be connected in parallel.

To limit the current and oscillations, resistances of about one ohm per volt are specified to be used in series with the spark gap, and may introduce a disturbing element.

As principal causes of variation in sparking tests may be considered:

Variation in wave form.

Transient voltages.

Growth of charge in the circuit.

Ionization of air.

Variation in Fundamental Wave Form. Spark gap voltages are proportional to maximum values of potential wave and the stress in the dielectric is also proportional thereto. We are, therefore, interested in the effective voltage only as a measure of the maximum voltage, and it is this fact that is largely responsible for the use of the spark gap. If, however, the testing apparatus including generator, transformer, and controlling devices, is properly designed and operated, a sine wave of potential in the discharge circuit may be assured, and measurement of effective values will then be sufficient.

Transient Voltages. It is not, however, variation in wave of fundamental frequency that is the chief disturbing factor, but transient voltages generated by the unstable condition of the test circuit. In most cases, these are of limited power and duration and have negligible effect on the dielectric unless high-frequency oscillations across a spark gap are set up. Transient voltages may jump the spark gap without starting dynamic arcs but setting up high-frequency oscillations of considerable power and destructive effect, or may establish an arc and would then be taken as a measure of the actual voltage of fundamental frequency. Thus it is seen that transient voltages are of negligible effect in the absence of a spark gap, but with spark gap connected, with or without test piece in parallel, may give misleading indications of the actual maximum of normal frequency voltage, and consequent stress in the test piece, or cause abnormal stresses by high-frequency oscillations.

Growth of Charge. The capacity of a condenser varies with the frequency, depending on character of dielectric and becoming less as frequency increases, due to absorption.

It has been observed during high tension tests that the charge seems to increase with time at constant voltage and frequency, and that at irregular intervals a critical point is reached, causing flash over and high frequency discharges at spark gap in parallel, or at some weak point in the test piece.

This can occur without causing a dynamic current to follow, and the length of spark gap is then not a measure of the normal frequency high-tension voltage. If the voltage is raised very rapidly it may be carried past the point of high-frequency discharge, and a genuine arc produced at the spark gap at a normal frequency voltage corresponding to its length, and considerably in excess of that first observed. This second higher voltage is then taken as the correct one.

Example. A high non-inductive resistance in parallel with spark gap and test piece tends to prevent abnormal rise in voltage. The following results were noted in testing three high tension transformer terminals in parallel each covered with tinfoil and thus having considerable capacity. The generator shown in Fig. 3 and a transformer similar to Fig. 5 were used. Resistance consisted of glass tubes filled with distilled water. Effective voltage by conversion ratio = 69300, corresponding to 5.6 in. (142 mm.) by A.I.E.E. spark gap curve.

Conditions	Voltage by spark gap
Spark gap alone	86000
Spark gap and resistance in parallel	73800
Spark gap and terminals in parallel	84000
Spark gap, terminals, and resistance in parallel	79000

Each voltage is the average of five to seven trials, the arcing distance being determined by first setting voltage by voltmeter and then closing gap till breakdown occurs.

As seen, the longest gap is broken with spark gap alone connected, and the shortest with resistance alone. Current in resistance is 0.05 ampere or one-tenth full load on transformer. Core loss is about 1200 watts; current taken by terminals is 0.03 ampere.

This example shows the variation that may occur between different trials under identical conditions, and also those due to slight changes in conditions.

Wave forms of voltage and current of test circuit are shown in Fig. 4. For taking voltage wave, the oscillograph was connected in series with the water resistance.

The average variation of spark gap voltage from conversion voltage is plus 4500 to 16700 volts, or a maximum of 23.3 per cent.

The maximum individual variations are from minus 4800 to plus 18200 volts, or a maximum of plus 26.2 per cent.

The spark gap undoubtedly gives fairly accurate measurements of the maximum instantaneous voltage except possibly for very high-frequency oscillations of small energy. As ordinarily used, however, its indications are interpreted as representing the effective value of a sine wave having a maximum value corresponding to the spark length. As the spark length depends on the maximum instantaneous voltage only, this may lead to large errors.

In the example given the effective values of the voltage must have been nearly the same throughout, the oscillations which broke the spark gap being of too high a frequency to have much

influence on effective values. As given, however, the figures represent effective values and thus give a very misleading idea of the actual conditions.

Ionization of Air. Ionization of the air will also affect the indications of the spark gaps. This will depend on circumstances as time of application of stress, form and arrangement of high-tension circuit, amount of air circulation, etc.

Conclusions. The chief arguments for the spark gap which, as I believe, have lead to its adoption by the A.I.E.E. are, that it measures the maximum potential and that in many cases no better method is available.

For laboratory purposes in connection with ordinary tests on small test pieces, which are alone under consideration, it should be easily possible to provide a sine wave generator and a trans-

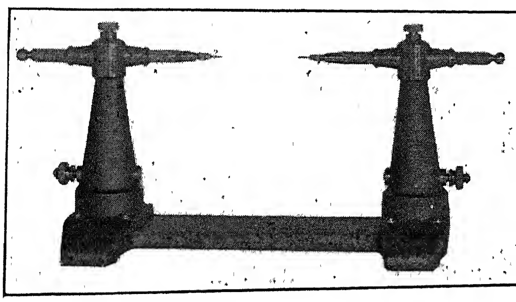


FIG. 12.—5-inch, 50,000-volt needle point spark gap with carborundum resistances in pillars

former of close regulation, thus eliminating the need for the spark gap.

Voltmeter Coil in High-Tension Transformer. This I consider the most nearly perfect method for determining the high tension voltage with convenience and accuracy. All that is required is a coil of few turns inserted symmetrically at middle of high-tension winding and connected thereto at the neutral point. A few turns of the regular winding could be used, but for mechanical reasons it is better to use a separate coil.

Connection of the windings is imperative, as it is not practicable to insulate the voltmeter coil against half the high-tension voltage, as is necessary if not connected.

Taps should be brought out at 25 per cent and 50 per cent of voltmeter coil winding to give convenient voltmeter readings at one fourth, one half and full potential.

Ratio of High Tension Voltage to Instrument Reading. It would seem superfluous to specify that this ratio should for the sake of convenience and accuracy be a simple number except for the fact that a most awkward multiplier is generally used as 50,000 to 110 = 454; 20,000 to 550 = 36.36; 10,000 to 108 = 92.6, etc.

The ratio in these cases should be

50,000 to 100 = 500 or 0.5 kilovolts per volt.

20,000 to 100 = 200 or 0.2 kilovolts per volt.

10,000 to 100 = 100 or 0.1 kilovolts per volt.

This arrangement eliminates mistakes and is more convenient than a chart or the slide rule.

The voltmeter should be dead beat. Magnetic damping of dynamometer types is satisfactory, but hot wire instruments have been found by me very convenient and reliable.

It is important that scale divisions be of nearly equal length throughout. A three-point switch for connecting the taps in voltmeter coil should be so placed as to be visible when taking readings, so that the ratio may always be accurately known. It is an advantage that voltage readings are independent of the position of series parallel switches on low-tension side of the transformer, depending only on position of voltmeter switch.

Accuracy. The accuracy of this method is very great. Although the voltmeter coil is concentrated at the middle of the high-tension winding, it embraces very nearly the same flux as the main winding. Therefore, the voltmeter readings are almost independent of the transformer reactance or ordinary variations in load and power factor.

The low-tension winding of the transformer Fig. 5, 6, and 7 consists of a cylinder closely surrounding the core. The high-tension winding is composed of a series of thin multi-layer coils with few turns per layer and arranged concentric with the low-tension coil. The voltmeter coil is similar to the high-tension coils and is inserted at the middle of the series and connected thereto.

Measurement of Energy Loss or Dielectric Hysteresis

With increasing potentials, the energy loss in the insulation, or "dielectric hysteresis" is becoming more and more a factor that must be taken into account in the design of high-tension apparatus. Its accurate determination is always difficult and frequently impossible, because of its small magnitude and the high voltage and low power factor involved.

Wattmeter in Low Tension Circuit. This requires accurate determination of losses in the high-tension transformer itself, which must be subtracted from all readings. With generator and transformer of proper design, with low exciting current and core loss in transformer, fairly good results are possible if the loss to be measured is large. All determinations of voltage and frequency must be extremely exact or large errors are introduced, as the losses to be determined are usually much smaller than the transformer losses. An additional difficulty is found in the change of wave form and core loss, due to load in the high-tension circuit, so that the transformer losses are not the same when loaded as when unloaded and the exact amount to subtract is uncertain.

Wattmeter in High Tension Grounded Circuit. This method, suggested by Dr. Steinmetz has been used with very satisfactory results. The series coil of a wattmeter is inserted directly into the high-tension circuit, preferably at the grounded neutral point, the winding being cut and the terminals brought out for this purpose. The potential coil of the wattmeter may be connected across a few turns of winding at the neutral point, or preferably to the voltmeter coil. Low reading commercial instruments are suitable for fairly large losses and the reflecting dynamometer for small losses.

To avoid danger from accidental open-circuiting of the high-tension winding at the neutral point, a short-circuiting device should be placed across the series coil of the wattmeter, connected as close to the transformer as possible. Two flat springs, may be used, pressed together and separated by thin paper, which punctures at about 500 volts.

Cathode-ray Power Indicator. This most elegant method, recently devised by Professor H. J. Ryan, appears to be superior to all others, especially for small measurements at high voltages. I have not yet had the pleasure of using it but purpose to make a practical trial immediately, as it is undoubtedly of great value in all high tension investigations.

Specific Capacity

The methods commonly used require standard condensers for comparison, the Wheatstone bridge, ballistic galvanometers, large test pieces, etc., and do not duplicate actual working conditions.

Great accuracy is not required, since the constants of ma-

terials vary over a wide range and the approximate average values on commercial materials are sufficient for the present purposes.

These determinations are easily made by a reflecting dynamometer ammeter inserted directly in the high-tension winding at grounded neutral point, and measuring sine wave current at normal frequency, the advantage of the method being that it determines the capacity of small test pieces under normal conditions, and is simple and direct.

Published results are of little more than academic interest since they do not represent commercial materials nor conditions, and apparently the constants of greatest value to the designer have never heretofore been measured.

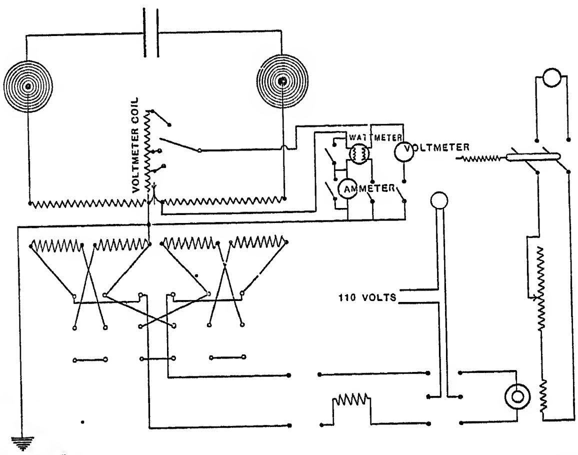


FIG. 13.—Arrangement and connections of apparatus for all high-tension tests

The complete arrangement for measurements of dielectric strength, arcing voltage, energy loss, and specific capacity, which I have found satisfactory is shown in diagram Fig. 13.

Cylinder controllers or switches for series parallel connection of four circuits are no doubt generally well known, but are also shown diagrammatically in Fig. 14 for the reason that I have never seen them published.

The following elements are shown in Fig. 13.

1. Exciter.
2. Field switch; normally held open by means of a spring, for the sake of safety.
3. Generator field rheostat; this should preferably be motor driven, so as to vary the high-tension voltage at a uniform rate.

4. Main switch, with auxiliary contact for lighting a red lamp as a danger signal; this may be arranged to illuminate voltmeter, for tests in the dark.

5. Automatic circuit breaker.

6. Series parallel switches on low tension side of transformers.

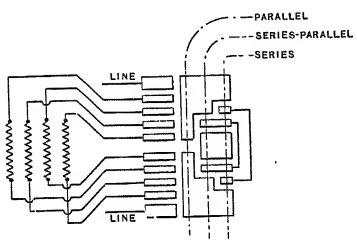


FIG. 14.—Series-parallel controller for four low-tension coils in transformer

7. Four low-tension coils of transformer, grounded.

8. High-tension winding of transformer, with loop brought out at grounded center for wattmeter and ammeter; short circuiting device for loop.

9. Voltmeter coil connected to high-tension winding at grounded center, and provided with taps and voltmeter switch.

10. Choke coils and testing terminals or electrodes.

11. Voltmeter, ammeter, and wattmeter connected for all measurements.

METHODS OF TEST—MATERIALS—TESTING DEVICES

GENERAL METHOD

Conditions of Test. To obtain exact and definite results all the conditions of test must be accurately known to the smallest detail. As, in general, the results of test are desired simply to show the value of the material under actual working conditions which naturally are variable and indefinite, it becomes necessary to adopt a standard, and as nearly as possible, a simple ideal method, which may be relied upon to give comparative results, and will permit easy and clear mathematical treatment.

The previous history of test piece, its precise condition, its form, size, and thickness, form and intensity of electrostatic field, temperature, time, frequency, and whether tested in air or under oil, may all have great influence on the results and must be taken into account.

Preparation of Test Piece. Since the presence of water is the greatest source of variation in the electrical qualities of insulating materials, it is necessary that all that are liable to absorb water should be thoroughly dried and waterproofed before testing. Liquids are best dried by filtering through dry blotting paper in a filter press.

Special tests require special treatment and testing devices,

which may be different for each case, hence will not be further considered here, though the above general principles apply to these also.

Standard tests, however, should be standardized in every particular, including the testing devices, and I here purpose to describe some of the methods, test pieces, and testing devices which I have found satisfactory.

Range of Conditions. It is desirable that tests be made under normal conditions, representing the general average of practical use, and also under the two extremes or limiting conditions, particularly of temperature, as in the majority of cases the temperature of operation of insulated apparatus, covers a wider range and with greater resultant effect on the properties of the insulating material, than any other single variable.

Temperature. High tension apparatus may operate over a temperature range of 150 deg. cent., or from −25 to +125 deg. cent., the lower limit being found in oil switches and similar apparatus generating little heat and located out of doors, and the upper limit in steam turbine generators and transformers operating at overload in heated power stations. These are the extreme conditions, and to represent standard practice, tests might be made at three temperatures as follows:

25 deg. cent. representing normal room temperature.

65 deg. cent. representing normal temperature rise of 40 deg. cent.

100 deg. cent. representing upper limit for transformers and turbine generators.

Heretofore the initial temperature of the test piece only has been considered. The heating effect of the stress, depending on the duration of test, and its results, varying with the facilities for heat dissipation, have a vital influence on the results of test and are extremely difficult to control and allow for. The above considerations apply equally to tests for dielectric strength, arcing voltage, hysteresis and specific capacity.

TIME

Test for Dielectric Strength and Arcing Voltage. The results will largely depend on the time of application of stress in all materials which exhibit an energy loss and consequent heating. The loss may be due to dielectric hysteresis as in solid organic compounds, to conduction as in all materials containing traces of water, and in the most general case to both.

If free from water, dielectric hysteresis alone need be considered. This is greatest in solids and least in liquids, viscous materials occupying a position midway between the two.

In general the puncture voltage will decrease with increase of time of application of stress, and it then becomes necessary to determine the complete time-versus-puncture-voltage curve.

Such curves show wide variations for different materials and often for the same material, or for any slight change in the conditions of test, and must be interpreted with the greatest care.

It is necessary, however, to have some basis for comparison and the following methods have been used and are recommended.

Instantaneous Tests. Voltage is applied beginning with a low value, not over one half of puncture voltage, and raised slowly and steadily till puncture occurs.

The total time occupied obviously varies somewhat but should be at a rate permitting voltage to be read to an accuracy of about 1 per cent of final voltage.

This method is suitable only for comparative results where great accuracy is not required, and is more particularly adapted to transformer oil and thin sheet insulation. Heating effects are negligible.

One Minute Tests. This method should be used for the majority of all tests. It is a step by step method, the voltage as before being applied at a low value, held constant for one minute, then increased slowly by a small percentage, again held constant for one minute and so on till puncture occurs. Heating effect may be considerable.

The initial voltage should be about 75 per cent of the puncture voltage, and the increments about 5 per cent each, the aim being to continue the test for three to five minutes.

Time Tests. Beginning with the instantaneous test, successive tests are made at decreasing voltages, each being maintained constant till puncture occurs, the curve being continued till the voltage approaches a constant value. Heating effect may be very marked and have a most important influence on results.

Test for Arcing Voltage. Results will not be greatly affected by time of test, except as this determines the temperature and consequently the specific capacity.

Tests should be made somewhat as in the " one minute test ", each voltage being maintained till the effects become sensibly constant, the final increment of voltage being very gradual.

Test for Energy Loss. The time of application of stress affects the energy loss principally as it influences the temperature of test piece. For complete information it is necessary therefore, to determine the curves of energy loss versus both time and temperature, at or between the limits of 25 and 100 deg. cent.

Test for Specific Capacity. The considerations of the last paragraph apply equally to tests of capacity.

FREQUENCY

The range of commercial frequencies—25 to 60 cycles—is too limited to have great influence on the results in standard tests and heretofore I believe it has not been customary to make any difference in the insulation of apparatus for variations in operating frequency over this range.

Test for Dielectric Strength. Results will vary slightly with the frequency but principally due to variation in energy loss and consequent heating, the higher frequency leading to a lower puncture voltage.

Test for Arcing Voltage. Results will vary with frequency, as this determines the charging current, and to a large extent, the "static" discharges and creeping effects. No great difference is to be expected between 25 and 60 cycles, however, and tests should be made at 60 cycles, so that results may be on the safe side.

Test for Dielectric Hysteresis. Results will depend on frequency and it may be necessary to make tests at both 25 and 60 cycles.

Test for Specific Capacity. Results will scarcely be affected by a variation in frequency between 25 and 60 cycles, the lower frequency tending to give higher values of capacity due to absorption.

Measurements by the proposed method may more readily be made at higher frequency, such as 120 cycles, since a small condenser will then take a current of sufficient magnitude for accurate measurement on ordinary instruments.

Greater accuracy would also be made possible by the use of the familiar guard ring.

Great refinement in method is unnecessary in the present state of the art, particularly as the variations in different samples of commercial materials are sufficient to entirely mask small errors in method.

Conclusions. Tests for dielectric strength of materials for

use at 25 to 60 cycles should be made at the frequency of 60 cycles. Such errors as exist due to variation from normal frequency are negligible or on the safe side.

For exact determination of dielectric hysteresis and arcing voltage the normal frequency must be used, and for capacity measurements 60 to 120 cycles is suitable.

Test piece should be considerably larger than electrodes to avoid leakage at edges of disks, and measurements should ordinarily be made under oil to avoid corona and leakage, and to represent condition of actual use of the dielectric as in oil-filled apparatus.

Testing Devices—Form of Electrodes—Effect of Edges

Theoretically the edges of electrodes should be rounded to a large radius to avoid the increase of dielectric flux density due to sharp edges. However there is always question regarding what this radius should be and in the absence of standards, I have generally used *square*, but not *sharp* edges, the corners being rounded to an insensible radius.

Thin sheets such as varnished cloth, whether tested in air or oil, seem usually to puncture at the edges of electrodes unless the latter are well rounded. Hence, I have used rounded edge terminals for standard tests, but square edges for special tests on greater thicknesses or under oil.

The increased stress on corners of electrodes is, however, objectionable, and in consequence thereof, failure of the dielectric tends to occur at this point. It is my intention to adopt electrodes with corners rounded to a radius equal to one tenth of the diameter of the flat face, for all standard tests for dielectric strength of flat sheets and plates.

Insulating Medium. All tests must be made either in air or under transformer oil and often in both ways, the results usually being quite different for the two cases. Obviously the conditions of test should as closely as possible resemble those of actual use, the best method to adopt depending on circumstances.

Insulating materials for high tension work are generally used under oil, and tests in air are impracticable owing to liability of arcing around the test piece, unless the latter is very large. The effects of immersion may be briefly discussed.

Effect on Test Piece. The electrical properties of insulating materials permeable to the oil are in general improved by impregnation and they should therefore, be thoroughly saturated before testing.

If the properties in a normal unimpregnated condition are required tests must be made in air, or immediately after immersion, or the material may first be rendered oil proof by a thin coating of lacquer or similar material of negligible influence on the other properties.

The good effect of saturation will largely be lost if test is made in air as the stress will drive the oil out of the material to some extent. This is especially noticeable with oiled pressboard, one of the best known insulators, in which the dielectric strength is nearly twice as great under oil as in air.

In laminated materials, the filling of the interstices with oil will also have an influence on results.

Effect on Electrostatic Field. The general effect of oil immersion is to eliminate corona and static discharges over the surface of test piece, to render the form and intensity of electrostatic field more definite and uniform and to concentrate it at edges of electrodes.

Effect of Temperature. This is very marked and consequently of great importance, especially in long time tests, a large volume of oil tending to maintain a constant temperature through out.

Tests at the different standard temperatures are thus readily made under oil, the oil being brought to the desired temperature before making test.

MATERIAL

Form. The material under test will usually be in one of the following forms: (1) liquids, (2) thin sheets and flat plates, (3) tubes, (4) miscellaneous.

Size. The puncture voltage of insulating materials depends more or less on the size of the area under stress, since the larger the area the greater the chance of including abnormally weak spots; therefore, this area should be as large as can conveniently be used.

Thickness. The thickness of commercial insulating materials usually lies between 0.001 in. and 2 in. (0.0254 and 50.8 mm.) and by far the greater proportion between 0.01 and 0.5 in. (0.254 and 12.7 mm.). Tests are most often required on single layers and multiple layers up to a total thickness of 0.5 in. (12.7 mm.)

The dielectric strength in general varies between the square root and first power of the thickness, for either single or multiple

layers, hence, unless the law of variation is accurately known, the test must be made on the actual thickness under consideration.

Thin Sheets. Flat circular disks of various diameters with square or rounded edges are generally used as electrodes.

It is usually most convenient to test very thin sheets in air, and for this purpose the material may be placed horizontally between the ends of brass cylinders of suitable diameter and weight, the lower cylinder being of any convenient height and the upper one made heavy enough to flatten out slight bends in the sheet and make uniform contact. The larger the area of the electrodes the better, but the dimensions are limited by practical considerations, it often being necessary to make a large number of trials on a small sample.

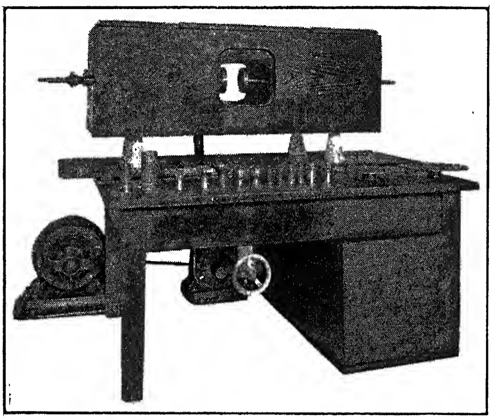


FIG. 15.—Spark gap for all high tension tests—showing different forms of electrodes employed and motor driven oil pump

For my own work there have been used brass cylinders 2 in. (50.8 mm.) in diameter with edges rounded to $\frac{1}{4}$ in. (6.35 mm.) radius, the lower cylinder being 1 in. (25.4 mm.) high and the upper about 5 in. (127 mm.) giving a pressure of 2 lb. per sq. in. (0.14 kg. per sq. cm.) area of face. These as well as a smaller pair are shown in Fig. 15 at the left end of table.

For standard tests of varnished cloth in single layers the upper electrode is used with a $\frac{1}{8}$-in. (3.1-mm.) brass plate 1 ft. (0.3 m.) square for the lower electrode, five or ten trials being made, the upper electrode being shifted for each trial.

Flat Plates: Spark Gap for Tests in Air or Oil. The apparatus shown in Fig. 15 is used for a great variety of standard and

special tests on all kinds of test pieces, in air or oil, hot or cold, and also for special tests on the oil itself, up to 200,000 volts.

The testing box contains three compartments, the testing compartment at center being provided with plate glass windows in each side, and smaller oil-filled compartments at each end, the latter serving merely to support and insulate the terminal rods.

The latter are 0.75 in. (19 mm.) in diameter, graduated in 20ths of an inch and sliding through heavy brass tubes supported in the ends and partitions of box. Graduated screw collars on ends of tubes permit measurement of distance between electrodes to 0.01 in. (0.25 mm.)

The inner ends of rods are drilled for needles, and a large number of electrodes of different sizes and shapes are also furnished and arranged to slip over the ends of rods.

These are shown on the table in front of test box. The large disks at the right are 10 in. (25.4 cm.) in diameter and are used for measurements of specific capacity. Flat disks with square (not sharp) edges are provided of 1, 2 and 4 in. (2.54, 5.08 and 10.16 cm.) diameter, the latter being shown in position on the rods, and generally used when size of test piece permits.

The end compartments of the box are always kept filled with oil, while the middle or testing compartment, is filled as required from the storage tank beneath, by means of the motor-driven centrifugal pump, shown connected to the box by rubber hose. The opening of a valve in this pipe, with pump stationary, allows the oil to flow by gravity backward through the pump to the storage tank.

For high temperature tests, the oil is heated by means of small electric heating units immersed in the oil.

This outfit is very complete and extremely convenient, nearly all of the results of tests given under "Characteristics of Insulating Materials", being obtained with it.

Tubes. Insulating tubes must usually be tested under oil between a central conductor and an outside wrapping of heavy lead foil. Paper, varnished cloth, treated tape and similar materials may be conveniently tested when wrapped to the required thickness on round rods or tubes, and handled the same as tubes.

Results will obviously depend on the ratio of outside to inside diameter of insulation, the ratio for least maximum dielectric flux density for a given outside diameter being, as is well known, theoretically equal to $e = 2.718$.

If this ratio closely approaches unity the results will be comparable to those for flat disk electrodes, hence a diameter of

2 in. (5.08 cm.) for the rod or tube, with a thickness of 0.125 to 0.5 in. (3.17 to 12.7 mm.) for the insulation, are suitable proportions.

In my own work, rods of rectangular cross-section 0.5 in. (12.7 mm.) by 1.5 in. (38.1 mm.) (resembling the proportions of armature coils) and round rods 0.75 in. (19.05 mm.) diameter have generally been used, but brass tubes of 2 in. (50.8 mm.) outside diameter and 3/32-in. (2.38 mm.) walls have recently been adopted, and are recommended for standard tests.

Miscellaneous Shapes. Definite specifications can not be given for special tests, but the general considerations already given may be applied, the aim being to obtain either *ideal* or *working* conditions, as the case seems to demand.

Tests for Dielectric Hysteresis. My own experience with these tests is very limited and no method has yet been standardized, but the methods recommended with the spark gap and tubes would seem to be suitable.

Test for Specific Capacity. The large electrodes shown in Fig. 15 are used for these measurements, a voltage of 5,000 to 15,000 at 60 to 120 cycles on test pieces 0.125 to 0.250 in. (3.17 to 6.35 mm.) thick giving good readings on reflecting dynamometer. Still larger electrodes would be advantageous if the size of the testing box would permit.

Liquids. Transformer oil is by far the most important liquid to be tested and as the same device may be used equally well for nearly all liquids, the spark gap for oil testing need alone be considered.

This consists of an insulating containing vessel of small capacity, provided with suitable electrodes which may or may not be adjustable for arcing distance.

Ordinarily a constant distance is used so that all results may be directly comparable and a standard dielectric strength specified for the oil.

Three forms of spark gap are now in use:

Electrodes arranged vertically in cup.

Electrodes arranged horizontally in cup.

Electrodes arranged horizontally on separate frame dipping in cup.

The electrodes consist of balls, flat disks or a ball and disk. All are adjustable for arcing distance, although a constant distance of 0.15 or 0.20 in. (0.59 or 0.78 mm.) is generally used rendering adjustment unnecessary.

Quantity of oil required for test is from a pint to a quart

(0.47 to 0.94 liters), a number of trials being made on each sample (usually five) and average taken, the oil being stirred between successive trials.

The disadvantages of these types for rapid work in a testing laboratory are:

1. Adjustability is in most cases unnecessary.
2. A large sample of oil is required for test.
3. A number of trials must be made on one sample. The arcs have a serious effect on the dielectric strength of sample, tending to increase it by the burning out and driving off of impurities or to reduce it by carbonization of oil. Hence the first trial only is reliable. Each trial should be made on a separate portion of the oil.

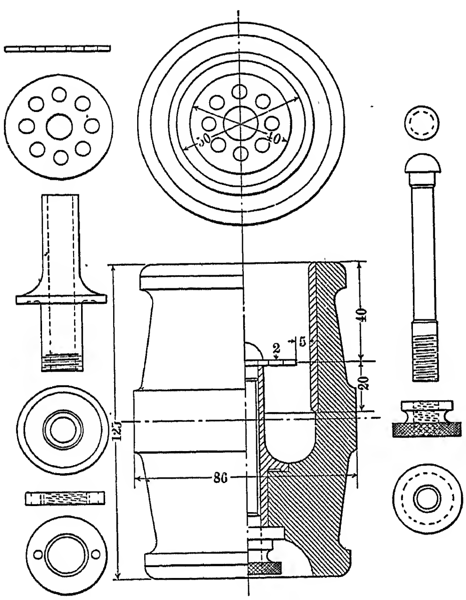


FIG. 16.—Proposed spark gap for oil testing—thin disk and tube model

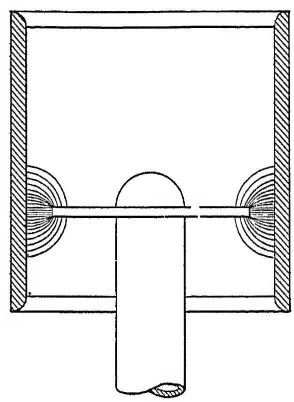


FIG. 17.—Proposed spark gap for oil testing—electrostatic field of thin disk and tube model

4. Distance between electrodes frequently is too small for accurate determination and maintenance.
5. Construction is not adapted to rapid and convenient use.
6. Voltage required is inconveniently high, 50,000 volts or more, necessitating large and expensive transformers.

In my own work it is often necessary to make five trials on each of 100 to 200 samples per day, hence the necessity for rapid manipulation is obvious.

I have designed about fifteen different forms of spark gaps,

seven of which have been built and tested. The final form is intended to overcome most of the above objections and is shown in half section in Fig. 16, which also exhibits the seven component parts. It consists of a hard rubber cup, the upper portion containing a brass tube lining as one electrode, and the lower supporting a brass column carrying at its upper end a brass disk concentric with the tube and forming the other electrode. All dimensions are in millimeters.

Inside diameter of tube..................	=50 mm.
Diameter of disk........................	=40 mm.
Thickness of disk.......................	=2 mm.
Length of gap...........................	=5 mm. = 0.1968 in.

Edges of the disk are square and eight holes are drilled through it to allow free oil circulation and prevent the collection of air bubbles underneath.

The considerations underlying this design are as follows:

Voltage. This can only be reduced to a convenient value by reducing the arcing distance, or by increasing the density of the electrostatic field by concentrating it at one electrode.

An error of 0.001 in. in 0.2 in. (0.025 mm. in 5.08 mm.) equals one-half per cent, hence 0.2 in. (5.08 mm.) is as small a gap as is desirable. It is also a standard in wide use. It therefore, becomes necessary to resort to a concentrated field.

Shape of Electrodes. The disk and tube seem to combine some desirable features:

1. Both electrodes are of simple symmetrical form easily made and measured and of great durability under use.

2. Disks of one and two mm. thickness with square or slightly rounded corners all gave the same results, hence slight variations in thickness of disk and condition of edge may be neglected.

3. The ratio; volume of oil under stress to total volume is very great.

4. The slight burning of the electrodes shows that arcing occurs over a zone about 15 to 20 mm. wide on the tube and 2 to 3 mm. back from edge of disk. This is somewhat surprising, as it would naturally be thought that arcing would always occur from the edge of disk, and especially from the corners.

This is not the case but arcing occurs anywhere within the limits above given, showing the great lack of homogeneity of the oil.

The effective area of the tube electrode is thus represented by a band 15 mm. in width and 157 mm. in length or 24 sq. cm. which is far greater than in any other proposed form of spark gap.

5. The cup and terminals are circular and thus perfectly symmetrical about a vertical axis.

6. There are no corners to retain dirt and it is easily kept clean. The hard rubber gives practically perfect insulation, is non-absorbent and neutral to the oil.

7. The voltage required is about 75 per cent of that for 0.2 in. (5.08 mm.) between 0.5 in. (12.7 mm.) disks, varying with the quality of the oil, as shown in Fig. 18 which gives the corresponding voltages for the two forms of spark gap. A 60,000-volt transformer is necessary with the standard gap of 0.2 in. (5.08 mm.) between 0.5-in. (12.7-mm.) disks, or 45,000 volts for the disk and tube gap.

8. No adjustment is needed, and as every part is circular in form, it is easily made and accurately set.

Method of Use. The spark gap is not provided with terminal connections but is intended to be slipped into a simple supporting frame, making contact by spring clips. For most convenient use it may be mounted on trunnions, and arranged to be inverted for emptying into a vessel beneath, automatically connecting to the spring clips when in a normal position.

A very small sample (155 cu. cm.) may be tested, but ordinarily only one trial should be made on each filling, the cup being filled and emptied for each shot. One quart (0.94 liters) of oil is sufficient for 7 trials. This assures that a normal representative sample is used for each trial. The sample should be thoroughly mixed immediately before pouring into the spark gap, as the impurities rapidly settle to the bottom, and care should be taken to eliminate air bubbles before testing.

The instantaneous method of test is always used though the results are affected in an irregular way by the time element. Apparently this is not due to dielectric hysteresis, but to transient voltages in discharge circuit, and to circulation of the oil in the cup, which eventually carries the impurities between the electrodes and tends to give lower readings of dielectric strength with increase of time.

I have not thoroughly investigated this point and it is possible that better results would be given by one minute tests but the regular adoption of this method is out of the question owing to the time and labor involved. Better results should also be obtained with less effort by repeating the test on additional samples.

Results. This spark gap has been thoroughly tested in comparison with a standard which consists of a wooden box holding

about one quart (0.94 liter) of oil, and provided with flat disk electrodes arranged horizontally in box, the disks being 0.5 in. (12.7 mm.) in diameter and placed 0.2 in. (5.08 mm.) apart, five trials made on each sample of oil.

The comparative results are shown by the curve of Fig. 18.

It must be admitted that for the higher voltages the disk and tube gap is not so sensitive to variations in quality of oil as is the double disk gap. This objection can be overcome by the use of a disk 1 cm. in thickness instead of 2 mm., with corners square, or rounded to 2 mm. radius, which gives the same sensitiveness as the standard double disk gap. This unfortunately sacrifices the advantages of the lower voltage required in testing, which was one of the main objects of the new design, but apparently a uniform field is required for sensitiveness in indications of the quality of oil.

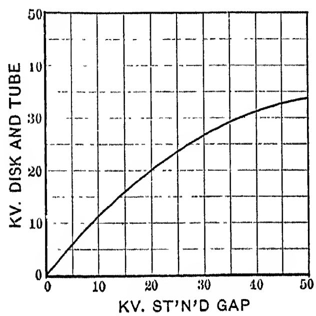


FIG. 18.—Comparison of standard spark gap with disk and tube

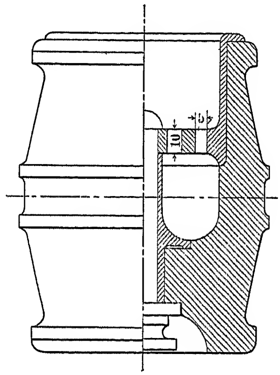


FIG. 19.—Proposed spark gap for oil testing—thick disk and ring model

The latest form of spark gap is shown in Fig. 19. In this a disk one cm. thick with square (not sharp) corners is used with a flat ring of one cm. width of face as the outer electrode, thus giving a nearly uniform field but requiring the same voltage as the double disk gap.

With this construction the volume of oil under test is still greater than with the thin disk, and the intensity of the electrostatic field is more nearly uniform. There seems to be no good method for greatly reducing the voltage required without loss of sensitiveness.

Accuracy. It must be admitted that no great accuracy can be

attained in oil testing, owing to the great variation in purity of the oil itself in different parts of the same sample or tank.

Variations of 50 per cent for successive shots on the same sample are common, and in general, the average of five trials cannot be considered accurate to within less than 10 per cent plus or minus. As already explained this may be due not so much to inaccuracy of method as to real differences in different portions of the oil itself, but it is none the less difficult to determine a definite value for the dielectric strength of a quantity of oil. If it is of extreme purity, successive tests (average of five shots each) may agree within 1000 volts.

Other Methods. The use of a small induction coil has been proposed in place of the transformer. I have not thoroughly tested this method and doubt its effectiveness.

Measurement of insulation resistance has also been tried but found impracticable owing to the extremely high resistance of the oil. The resistance also varies greatly with temperature and there seems to be no close connection between resistance and dielectric strength. The dielectric strength must be known, and it is the dielectric strength that must be measured.

Characteristics of Insulating Materials

General. It will be possible to present but a few general considerations, supplemented by some characteristic results of tests on commercial insulating materials.

In the study and comparison of these materials it is best to look for similarity and correspondence everywhere, rather than to emphasize slight and accidental differences which are much more likely to be due to variations in physical state, form, purity, amount of contained water, and methods of test, than to be inherent in the particular *kind* of material.

All insulating materials may be divided into a few classes, each covering broadly all materials of the same general characteristics, and if the group to which a given material belongs is known, its behavior as an insulator may often be predicted.

The literature of the subject is incomplete and unsatisfactory, the problem usually being attacked from the standpoint of physics rather than from that of engineering, and every investigator using different materials and methods.

Classification

The materials with which we are most concerned may be divided into the three chief classes, *viz.*, liquid insulators, viscous

insulators, and solid insulators; and obviously many materials may exist in any of these states.

Liquids. Fessenden states that "Practically all the fluids which are not simple elements, like mercury, have very high ohmic resistance, and all have practically about the same dielectric strength."

This agrees with my own experience, as I have always found approximately the same dielectric strength in all transformer oils, gasoline, benzine, cylinder oil, linseed oil, varnish, etc., if at normal air temperature and equally pure and free from water. Since it is practically impossible to determine the *exact* dielectric strength of a liquid, any characteristic difference would be difficult to detect if small, minute traces of water, which are generally present, having a far greater effect on the results than the difference in *kind* of liquid. Fine dust and dirt in suspension has a very deleterious effect on the oil, comparable to that of water in reducing the dielectric strength.

Carbon tetrachloride (CCl_4) has been suggested as a substitute for transformer oil, but is a very powerful solvent, and as such, may attack insulating materials, so that it is difficult to maintain its purity under use. Its dielectric strength, if pure, equals that of transformer oil, but it is rapidly reduced by arcing, each successive breakdown test giving lower results than the preceding.

In general, the dielectric strength of all insulating liquids at 25 to 100 deg. cent. equals 50,000 volts (for 0.2 in. or 5.08 mm. between 0.5-in. or 12.7-mm. disks) plus or minus 10,000 volts, depending almost entirely on the amount of contained water and dirt.

The dielectric strength of transformer oil when frozen *hard* is much greater than when liquid, and reaches its lowest value when in the viscous transition state between a liquid and solid.

The curve Fig. 21 represents the effect of water on the dielectric strength of oil when thoroughly mixed. It is probable that the reduction of voltage is here a maximum, and that the effect would be less serious if the oil and water were less thoroughly mixed.

The mixture was allowed to stand about five minutes after mixing and before testing to allow air bubbles to rise to the surface. Tests on dry oil, shaken and allowed to stand as specified, showed that the effect of air bubbles, if present, was negligible.

I have not yet measured the dielectric hysteresis of liquids but it is undoubtedly very low. The specific capacity of transformer oil has been found sensibly constant and equal to 2.5.

Viscous Insulators. In this class may be placed such materials as vaseline, mixtures of transformer oil with rosin, asphalt, etc., which seem to have the same dielectric strength as transformer oil.

Varnish may exist in a partly dried viscous condition on the inside of finished apparatus, and when in this state seems to possess the same dielectric strength at 20 deg. cent and 85 deg. cent. although when thoroughly dried, the dielectric strength is much reduced by the higher temperature.

In general, I have found the dielectric strength of viscous insulators, to be less than that of the same material in the dried or solid state, but to be unaffected by a rise in temperature from 20 to 85 deg. cent., apparently due to lower energy loss from dielectric hysteresis.

The dielectric hysteresis and specific capacity have not been measured but are probably between those for liquids and solid insulators. The results of long time tests under high voltage show great variations in heating, which may be due to the presence of water or other impurities.

Solid Insulators: Variations. These exhibit greater variations than either liquids or viscous materials, and also possess much greater dielectric strength, dielectric hysteresis and specific capacity.

Thickness. These variations are found not only between fundamentally different materials but also between different *thicknesses* of the same material. For example, pressboard is made in all thicknesses from 0.007 to 0.125 in. (0.177 to 3.17 mm.) the thinner sheets being much denser, harder and more highly finished than the thick, and the variations in dielectric strength between the different thicknesses may be as great as between entirely different materials. Practically, they *are* different materials mechanically, though made of the same stock and in the same manner.

These considerations also apply to many other materials.

Fibrous Materials: Treatment. Cloth, tape, paper, pressboard, wood, and to a smaller extent the chemical hard fibers, such as leatheroid, rawhide, and vulcanized fiber, can hardly be classed as insulators at all until they have been dried, and coated or impregnated with an insulating varnish or compound

which fills the pores and renders the surface waterproof. Hence nothing need be said regarding these materials in the undried and untreated state.

Hard Fibers. The chemical fibers are impervious to insulating liquids or compounds but freely absorb water. When dry they are fairly good insulators but to remain so must be immediately waterproofed.

Surface Coatings. A surface coating of insulating varnish increases the dielectric strength but slightly, unless the thickness of coat is large compared to thickness of material or the latter is a poor dielectric. This is shown in the case of varnished pressboard.

Color. Vulcanized fiber and many other solid insulators are commonly colored with bone black or iron oxide. The dielectric strength seems to be unaffected by either, contrary to the usual impression. Lamp black is a conductor and its use is fatal to insulation.

Hardness and Density. In general, the dielectric strength of fibrous materials increases with the hardness and density.

Wood. Hard wood thoroughly dried and impregnated with an insulating liquid or compound is an excellent insulator. Maple is considered best, but equally as good results have been obtained with cherry, ash and yellow pine.

For impregnation, transformer oil, paraffine and rosin have been used, depending on the use to be made of the wood, the oil treatment being suitable for wood to be used under oil, and paraffine or rosin if used in air.

Paper. Treated paper forms a large part of the insulation of high tension apparatus, particularly of transformers.

Parchment, horn fiber, and pressboard, are three of the best and most widely used, and in conjunction with mica, varnished-cloth, tape, and treated wood form the major part of the entire insulation.

Pressboard. The major insulation of all high-tension transformers consists of pressboard, either varnished or boiled in transformer oil. The latter simple and obvious method, seems to be a recent discovery, but one of great value as thereby the dielectric strength is increased above that of almost any other known material. It is particularly high for very short-time tests, a point of great importance where excessive transient voltages must be resisted.

Varnished pressboard has about one-half the dielectric

strength, the insulating power being almost entirely in the varnish film. For this reason the thicker material is not greatly superior to the thin, particularly as the latter is harder, more dense and more highly finished.

Pressboard is made from cotton rags and paper clippings in several grades, and has a thoroughly laminated structure, each 0.003 in. (0.076 mm.) in finished thickness representing a separate layer of pulp, hence impurities are not especially objectionable as they are confined to separate layers.

The principal defects arise from folds in the materials, which have been crushed by the calender rolls during the course of manufacture, thus destroying the mechanical and electrical strength of the finished pressboard.

Special Compounds. For best results, it is essential that electrical coils be thoroughly impregnated with solid insulating compounds.

For use in air, compounds composed of rosins, asphalt, etc., are suitable, but for oil-filled apparatus a material insoluble in the hot oil is necessary.

These compounds must be forced into the coils under heat and pressure, and obviously may melt and run out afterward if apparatus is operated at very high temperatures.

It is believed that the limit in the possibilities of vegetable gum compounds has about been reached, and that for future progress the synthetic gums or artificial rosins offer the best opportunities for improvement.

These compounds, being liquid in the original state, may be forced into the coils while cold. On baking the liquid becomes perfectly hard and solid, and is then insoluble in oil and cannot be remelted.

Variation of Dielectric Strength with Thickness. Why is not the dielectric strength of insulating materials proportional to thickness? The uniform experience with test pieces an inch (25.4 mm.) or less in thickness, shows that the puncture voltage varies between the first power and square root of thickness, and all attempts to prove otherwise, or to develop a universal formula have apparently failed.

Possibly variations in form of the electrostatic field, using identical electrodes, with varying separation to accommodate the different thicknesses, has something to do with it, but can hardly account for the great variations from a straight line law. The fact remains, however, and it is unsafe to calculate the dielectric

strength for a given thickness, from tests on a different thickness. Hence, no reliance can be placed on results given per centimeter, or per inch and based on tests of, say one mm. thickness.

Effect of Lamination. The best insulators have usually a finely laminated structure. This is shown in mica, pressboard, and all built-up insulations of cloth, tape, paper, etc.

The value of lamination may be explained in part as follows:

1. Weak spots are confined to one layer and are unlikely to line up throughout.

2. Material being discontinuous, there is less danger that a rupture in one portion will extend to another.

3. If used under oil, the interstices may be filled, thus adding to the strength and excluding air.

4. Thin materials are in general superior to thick in both mechanical and dielectric strength.

Mechanism of Rupture of Dielectrics under High Potential Stress. The exact action taking place during rupture is but imperfectly understood and there seems to be a tendency to lay too much stress on single aspects of the phenomena.

In the most general case it is probable that the following takes place:

1. A molecular strain in the dielectric corresponding to the "displacement", or condenser current.
2. Consequent heating by dielectric hysteresis.
3. Conduction by means of conducting impurities.
4. Conduction by ionization.

The prominence of each of the above will vary with the character of the dielectric, although in the majority of cases it would seem probable that all take place to some extent. Thus, provisionally, the action in each of the chief classes of insulators may be conceived as follows:

Gases—molecular strain and ionization.

Liquids—molecular strain; impurities; ionization.

Solids—molecular strain; hysteresis; impurities; ionization.

In solids, hysteresis is of great effect, and rupture may be almost entirely due to charring from the heat generated by the alternating stress. The dielectric strength of many of the best insulators is reduced 50 per cent by an increase in temperature from 25 to 100 deg. cent.

Arcing Voltage: Surface Creeping. Strictly speaking there is no such thing as the "creeping voltage" of an insulator, the voltage required to arc over a clean insulating surface being

nearly independent of the kind of material and character of surface, but determined by the form and arrangement of electrodes and insulation.

It depends indirectly on the capacity of the apparatus considered as a condenser, and the character of the dielectric (as air or oil) which is ruptured by the arc, every "creeping" test being also a puncture test, as is obvious.

Place two electrodes on a sheet of insulating material such as 3/32 in. (2.38 mm.) oiled pressboard about 3 inches (76.2 mm.) apart and apply voltage. If in air the arc will form at or near the surface of pressboard at about 50,000 volts. Now place terminals opposite each other on opposite sides of pressboard and 6 in. (152.4 mm.) from edge. Arc-over will occur at about 40,000 volts. Thus the "creeping" or "arcing" voltage of oiled pressboard is 50,000 volts for 3 in. (76.2 mm.), or 40,000 volts for 12 in. (304.8 mm.) as the case may be.

If two layers of pressboard are used, the arcing distance for the same voltage will be the same in the first case, but greatly reduced in the second, the *capacity* being reduced one half. Thus in designing insulations, such as separating flanges, the arc-over voltage may be increased more readily by making the flange thicker than by increasing the width.

This principle is simple and may often be applied to great advantage.

Summary

1. The principal high-tension tests of insulating materials are stated, and the requirements in testing apparatus defined.

2. Suitable generators, transformers and controlling and measuring apparatus are described and illustrated.

3. The spark-gap for measuring voltage is discussed and the voltmeter coil in transformer recommended.

4. Suitable methods of test are described. The adoption of standard methods and devices is recommended.

5. Spark-gaps for oil testing are discussed.

6. Some characteristics of insulating materials are discussed.

7. Results of actual tests are given in the form of curves.

I desire to acknowledge the great assistance rendered in the experimental work and preparation of this paper by Messrs. M. E. Tressler, M. G. Newman and C. R. Blanchard.

Conclusions

This paper chiefly represents the author's personal experience and opinions and is intended to be mainly suggestive, and to

excite interest in the general subject of high tension insulation and methods of testing, rather than to offer definite solutions of the problems presented.

Results of Tests. The following curve sheets represent some results of tests made by the methods and apparatus herein described and recommended.

Great accuracy in this work is at present unattainable, nor is it claimed for the results given. Some of the curves were made especially for this paper and represent but a single series of observations, while others were made some time ago and have since been confirmed and modified by many additional tests. The latter are ideal curves and do not represent any one series of tests but are believed to be reliable.

The figures given for accuracy represent the probable variations of single points in a series of tests. They apply particularly to the middle of curves, the accuracy being less for lower voltages and greater for higher.

The values of specific capacity given represent the average of a number of measurements on different samples. Individual variations are about 20 per cent plus or minus.

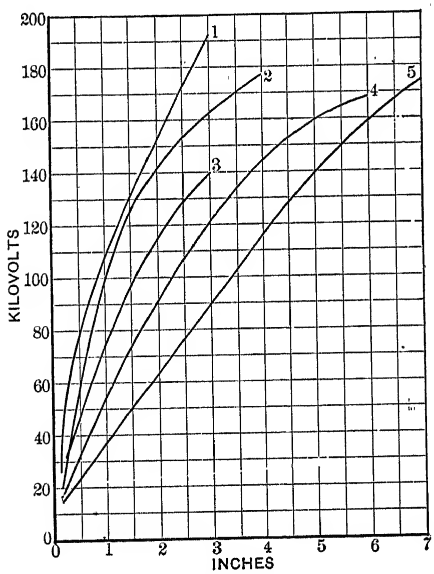


FIG. 20

DIELECTRIC STRENGTH OF OIL WITH VARIOUS SHAPES OF ELECTRODES

Curves.—For 4-in. disks—2-in. balls—1-in. blunt conical points—needle points—4-in. disk and needle point.
Material.—Heavy transformer oil.
Dimensions.—Specific gravity 0.868—viscosity 100 Saybolt at 40 deg. cent.
Composition.—From Pennsylvania crude.
Treatment.—Filtered through dried blotting paper.
Method of test.—Beginning at lowest voltage, each curve is taken up to highest voltage and down again—about 10 to 15 points being taken on each curve. Standard test on oil at beginning and end shows that quality remained nearly constant.
Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—60. Wave—sine.
No. of trials.—Each point, about five.
Accuracy of curve.—Plus or minus 10 per cent.
Characteristics.—Puncture voltage depends very largely on shape of electrodes. Curve 1—using 4-in. disks. Curve 2—using 2-in. balls. Curve 3—using 1-in. blunt conical points. Curve 4—using needles. Curve 5—using 4-in. disks and needle.
Specific capacity.—2.5 from 25 to 100 deg. cent.

Notes.—These are standard curves, suitable for use in design. They are based on the same data as those given in the paper on "The Dielectric Strength of Oil" (TRANS. A.I.E.E., 1909) by H. W. Tobey.

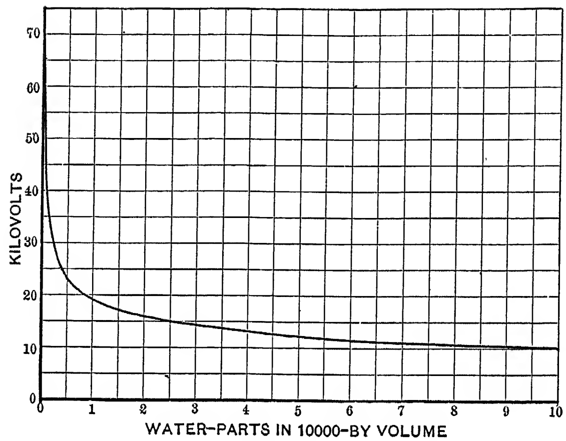


FIG. 21

WATER IN TRANSFORMER OIL

Curves.—Dielectric strength versus content water.
Material.—Heavy transformer oil.
Dimensions.—Specific gravity, 0.87—viscosity at 40 deg. cent. =100 Saybolt.
Composition.—From Pennsylvania crude.
Treatment.—Oil is first filtered through dry blotting paper, and oil and water then emulsified by mechanical shaker.
Method of test.—Standard spark gap 0.2 in. between 0.5-in. disks—two separate emulsions—four samples of each—five trials on each sample.
Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—75. Wave—sine
No. of trials.—each point, 40.
Accuracy of curve.—plus or minus 5 per cent—believed to be the most reliable ever published
Characteristics.—Extremely rapid reduction of dielectric strength by minute quantities of water—under 0.01% if thoroughly mixed.
Specific capacity.—dry oil =2.5 at 25 to 100 deg. cent.
Notes.—Practically identical results obtained on light oil—specific gravity 0.85—viscosity at 40 deg. cent. =40 Saybolt.

Equation of curve.— $y = \dfrac{19.2}{x^{\cdot 284}}$

OILED PRESSBOARD

Curves.—Dielectric strength versus thickness of sheet.
Dimensions.—0.011 in. to 0.122 in. thick.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials, hence is not very reilable, but shows typical results.
Characteristics.—Material is variable; results depend largely on time of application of stress.
Specific capacity.—4.9 at 20 to 25 deg. cent. under oil.

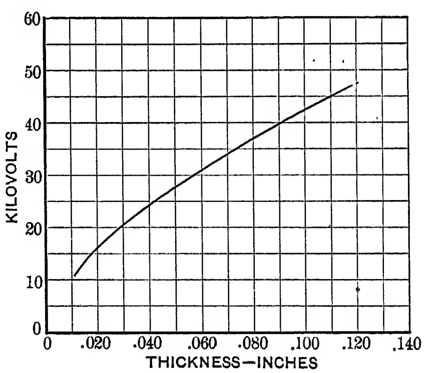


FIG. 22

Notes.—Total time of test is about five minutes (average) giving rather low results.

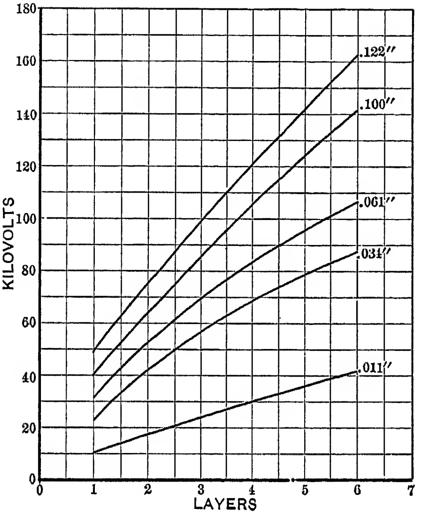


FIG. 23

OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thicknesses of board.
Dimensions.—0.11 in. to 0.122 in. thick—one to six layers.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials, hence is not very reliable, but shows typical results.
Characteristics.—Material is variable; results depend largely on time of application of stress.
Specific capacity.—4.9 at 20 to 25 deg. cent. under oil.
Notes.—Total time of test is about 5 minutes (average) giving rather low results.

VARNISHED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thicknesses of board.
Dimensions.—0.035 in., 0.067 in. and 0.097 in. thick—one to six layers.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and given two coats of varnish.
Method of test.—Between square edge flat disks 4 in. in diameter under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave-sine.
No. of trials.—Each point, one to four.
Accuracy of curve.—10 per cent plus or minus. Curve is based on but a few trials hence is not very reliable but shows typical results.
Characteristics.—Dielectric strength low but fairly uniform, depending largely on varnish film; nearly proportional to total thickness within limits of tests.

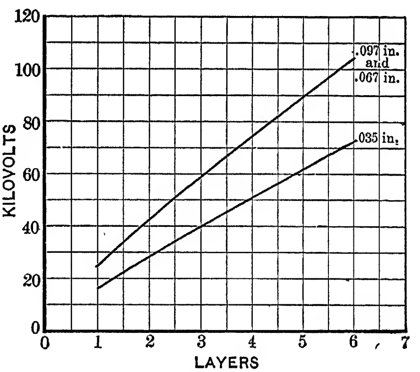


FIG. 24

Specific capacity.—2.9 at 20 to 25° C. on 0.097-in. board.
Notes.—Same results were obtained on 0.067-in. and 0.097-in. board. Thin board is superior to thick in hardness, density and finish, thus compensating for difference in thickness. Thickness given is as actually measured after varnishing.

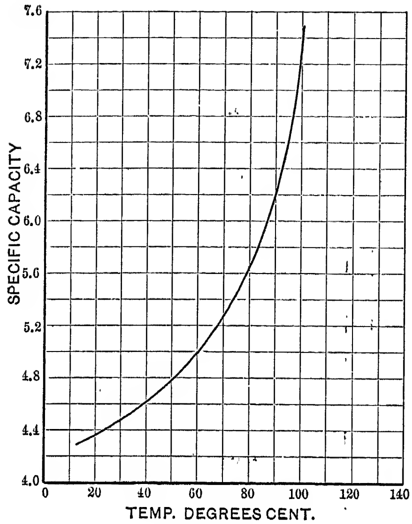


FIG. 25

SPECIFIC CAPACITY OF OILED PRESSBOARD AT DIFFERENT TEMPERATURES

Curves.—Specific capacity versus temperature.
Dimensions.—0.125 in. thick.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square cornered flat disks 10 in. in diameter under oil at different temperatures.
Temperature.—13 to 100 deg. cent. Frequency—60. Wave—sine.
No. of trials.—Each point, one.
Accuracy of curve.—5 per cent plus or minus.
Characteristics.—Specific capacity increases very rapidly with rise of temperature.
Specific capacity.—4.3 at 13 deg. cent. to 7.5 at 100 deg. cent.

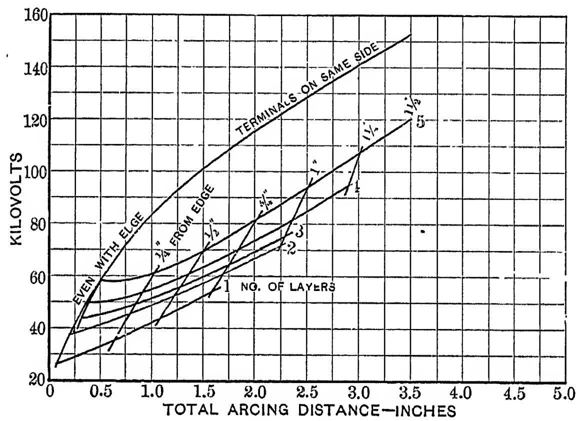


FIG. 26

"CREEPING" OR ARCING VOLTAGE ON OILED PRESSBOARD

Curves.—"Creeping" voltage between electrodes on same or opposite sides of board—using different number of layers of board.
Dimensions.—0.095 in. thick.
Composition.—Cotton rags and paper clippings.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between round flat electrodes 4 in. in diameter or resting on flat semicircular electrodes of 2-in. radius the rounded faces of electrodes facing each other on same side of board. All electrodes have square corners where in contact with board. Tests under oil.
Temperature.—20 to 25 deg. cent. Time—instantaneous. Frequency—60. Wave—sine.
No. of trials.—Each point, five to ten.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Curves show the great difference in arcing voltage for a given distance, depending on whether terminals are on same or opposite sides of board.
Condenser capacity.—Practically zero with terminals on same side of board and very large when on opposite sides.
Notes.—This shows that the "creeping" voltage is not a constant of the material but depends on the arrangement of parts.

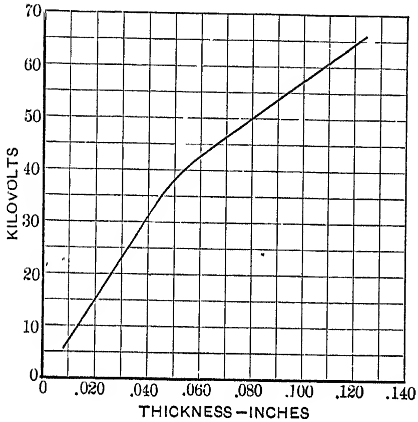


FIG. 27

DIELECTRIC STRENGTH OF OILED PRESSBOARD

Curves.—Dielectric strength versus thickness of sheet.
Dimensions.—0.007 in. to 0.125 in. thick.
Composition.—Cotton rags.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, large number.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Extremely high dielectric strength.
Specific capacity.—4.3 at 20 to 25 deg. cent. under oil.
Notes.—This is a standard curve based on many tests.

DIELECTRIC STRENGTH OF OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.
Dimensions.—One to six layers of sheets, 0.031 in. to 0.125 in. thick.
Composition.—Cotton rags.
Treatment.—Dried and boiled in transformer oil.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, small number.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Dielectric strength of 0.031-in. is proportional to total thickness but of thicker sheets increases at slower rate.
Specific capacity.—4.3 at 20 to 25 deg. cent. under oil.
Notes.—This is a standard curve based on long experience.

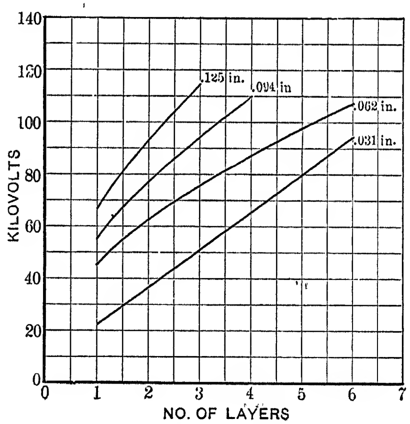


FIG. 28

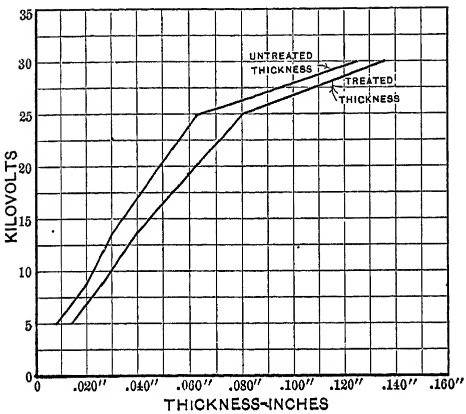


FIG. 29

DIELECTRIC STRENGTH
VARNISHED PRESSBOARD

Curves.—Dielectric strength versus thickness sheet. Curves represent thickness varnished and unvarnished. Dielectric strength is for varnished only

Dimensions.—0.007 in. to 0.125 in. thick before treatment.

Composition.—Cotton rags.

Treatment.—Dried and given two to four coats linseed oil and gum varnish depending on thickness.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, large number.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Curve is broken line because the different thicknesses vary in character and treatment. Number of coats of varnish increases with thickness.

Notes.—This is a standard curve based on long experience.

DIELECTRIC STRENGTH
VARNISHED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.

Dimensions.—0.007 in. to 0.125 in. thick before treatment.

Composition.—Cotton rags.

Treatment.—Dried and given two to four coats linseed oil and gum varnish, depending on thickness.

Method of test.—Between square cornered flat disks under oil.

Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.

No. of trials.—Each point, one series of tests.

Accuracy of curve.—10 per cent plus or minus.

Characteristics.—Dielectric strength nearly proportional to total thickness.

Notes.—This is a standard curve.

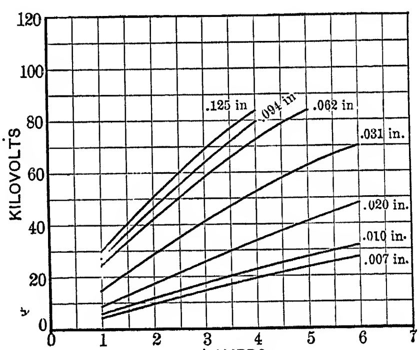


FIG. 30

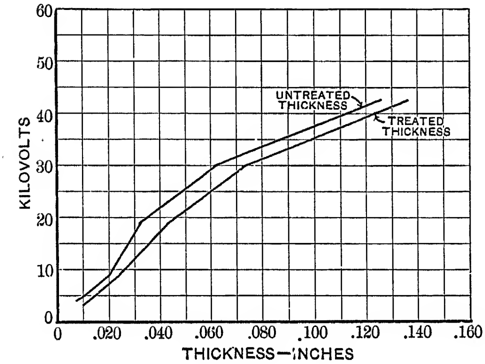


FIG. 31

DIELECTRIC STRENGTH OILED PRESSBOARD

Curves.—Dielectric strength versus thickness sheet; curves represent thickness treated and untreated; dielectric strength is for treated only.
Dimensions.—0.007 in. to 0.125 in. thick, before treatment.
Composition.—Cotton rags.
Treatment.—Dried; boiled in linseed oil; the 0.031-in. to 0.125-in. board also received two coats varnish.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one series of tests.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Curve is broken line because the different thicknesses vary in character and treatment.
Notes.—This is a standard curve based on long experience.

DIELECTRIC STRENGTH OILED PRESSBOARD

Curves.—Dielectric strength versus number of layers of different thickness.
Dimensions.—0.007 in. to 0.125 in. thick before treatment.
Composition.—Cotton rags.
Treatment.—Dried; boiled in linseed oil; the 0.031-in. to 0.125-in. board also received two coats varnish.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one series of tests.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Dielectric strength nearly proportional to total thickness.
Notes.—This is a standard curve.

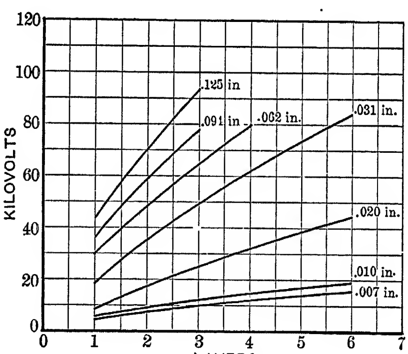


FIG. 32

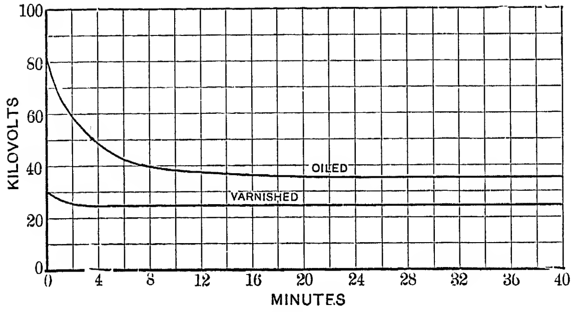


FIG. 33

TIME TEST; OILED OR VARNISHED PRESSBOARD

Curves.—Dielectric strength versus time for oiled or varnished pressboard.
Dimensions.—0.94 in. thick.
Composition.—New cotton rags.
Treatment.—Oiled pressboard, dried and boiled in transformer oil; varnished pressboard, dried and treated with four coats varnish.
Method of test.—Between flat, square cornered disks, under oil. A definite voltage applied and held till puncture occurs. Spark gap contains about 15 gals. of oil, hence heating is slight.
Temperature.—20 to 25 deg. cent. Time—until rupture. Frequency—60. Wave—sine.
No. of trials.—Oiled board, average of two curves, 10 points each.
Accuracy of curve.—Plus or minus 10 per cent on oiled pressboard; plus or minus 20 per cent on varnished pressboard.
Characteristics.—Oiled board gives definite results on a smooth curve; varnished board gives very irregular results; curve shows general tendency only.
Specific capacity.—Oiled board =4.3 under oil at 20 to 25 deg. cent.
Notes.—As opportunity for cooling was excellent, the heating effect must have been very small. Results under heat may be expected to be very different.

INCREASE OF ENERGY LOSS IN INSULATION WITH INCREASE OF TEMPERATURE

Curves.—Loss in the insulation of a high tension transformer.
Material.—Mainly oiled pressboard.
Method of test.—Loss measured by wattmeter at middle of high-tension winding as shown in Fig. 13.
Temperature.—23 to 58 deg. cent. Time—11½ hours. Frequency—60. Temperature of oil taken at top.
No. of trials.—Each point, one.
Characteristics — Losses increase slightly faster than square of temperature rise.
Note.—Voltage wave has an 11th harmonic, 12 per cent of the fundamental.

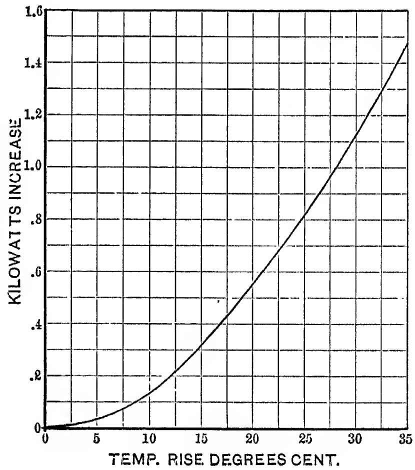


FIG. 34

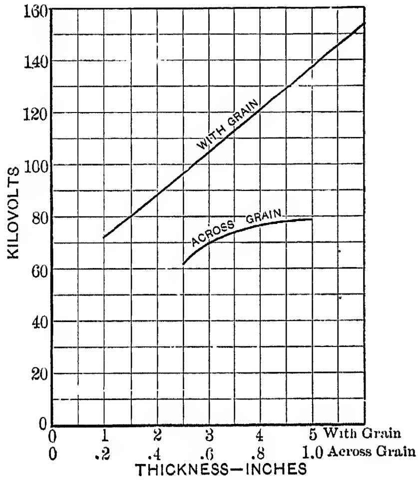


FIG. 35

DIELECTRIC STRENGTH
OILED WOOD

Curves.—Dielectric strength with and across grain, versus thickness wood.
Material—Hard maple.
Dimensions.—½ in. to 1 in. across grain; 1 in. to 6 in. with grain.
Treatment.—Across grain, boiled in transformer oil under vacuum; with grain, dried under vacuum, boiled at atmospheric temperature.
Method of test.—Between square cornered flat disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
No. of trials.—Each point, one to three; three points across grain; 5 points with grain.
Accuracy of curve.—10 per cent plus or minus.
Characteristics.—Dielectric strength across grain increases much slower than thickness but with the grain is proportional to thickness.
Specific capacity.—Across grain =4.1 at 20 to 25 deg. cent. under oil.
Notes.—Test with and across grain on samples treated by different methods a long time apart. Wood seems to be identical in quality however

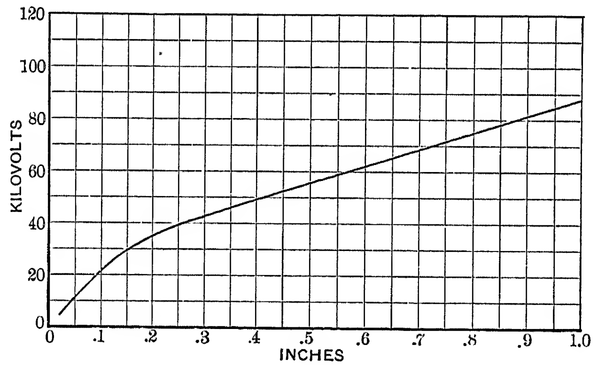


FIG. 36

DIELECTRIC STRENGTH OF HARD FIBER

Curves.—Measured on single thicknesses.
Dimensions.—0.031-in. to 1-in. sheets.
Composition.—Chemical hard fiber.
Treatment.—Dried before testing.
Method of test.—Between flat, square cornered disks under oil.
Temperature.—20 to 25 deg. cent. Time—one minute. Frequency—60. Wave—sine.
Accuracy of curve.—About 10 per cent plus or minus.
Characteristics.—Results depend largely on dryness of fiber.
Notes.—Results on fiber of different colors seem to be identical.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers February 14, 1911.

HYSTERESIS AND EDDY CURRENT EXPONENTS FOR SILICON STEEL

BY W. J. WOOLDRIDGE

It is my intention to bring before the Institute as briefly as may be, the apparent changes in general direction of curves required for predetermining core losses of apparatus, especially transformers, in which silicon steel is used.

When this alloyed steel first came into use, some years ago, curves were drawn up based on losses found in samples tested at 5,000 B and 10,000 B and retaining the use of the Steinmetz exponents which had for many years stood as approximately correct values for commercial electrical sheet steel, *viz.*, eddy current loss increasing as B^2 and hysteresis loss increasing as $B^{1.6}$.

It was quite natural that this material should first be used in transformers both because of the constant demand for lower core losses, the prospect of more compact designs and also because of the mechanical qualities of silicon steel.

With ordinary steel the limit of design for transformers was along the line of heating. That is to say, the limit was the watts per square inch of effective radiating surface.

With the lower watts per pound of the new steel an increase in core density above that generally used in the old material seemed allowable and was also desirable in order to offset the higher cost per pound of the steel. Core loss curves made on such transformers showed the material at low densities to be in accord with design curves, but at medium densities (12,000 B for instance) the loss was considerably above anticipated results.

In seeking the cause of the trouble the well established exponents which had proven satisfactory for so long, were not at

first considered. The test curves when carried further, to relatively high densities, showed a continued increase but not logarithmic. It was noted in such cases that the power factor decreased rapidly, this decrease coinciding in a marked degree to

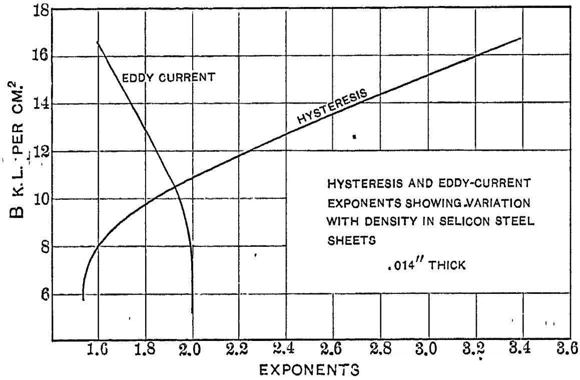


FIG. 1

the increased core loss as shown by the wattmeters. The higher loss was, therefore, assumed to be due at least in part to incorrect wattmeter readings and in part to a possible change in wave form.

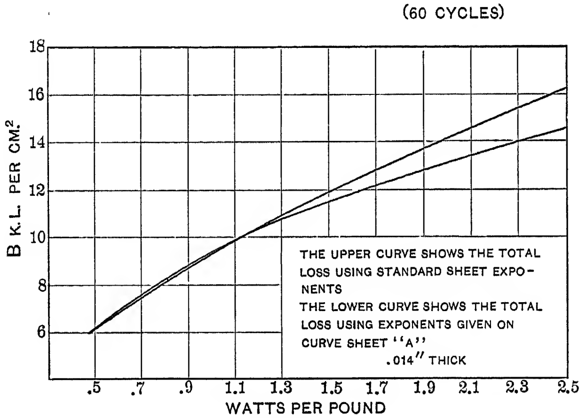


FIG. 2

Later, the development of the iron clad instrument, giving correct readings at low power factors, showed that the premise regarding the effect of incorrect wattmeter readings to be largely a wrong one. Tests on a small core carefully tested on sine

wave and then used in conjunction with the transformer under test, enabling a ready and convenient correction for wave form, gave further evidence that the high core loss at high densities was inherent.

Careful tests on variously proportioned cores, such as rings without gaps, rectangular cores, and complete transformers, were found to agree closely and finally led to the inevitable conclusion that the exponents regularly used for ordinary steel did not hold for silicon steel.

This has been confirmed by several other investigators and has been published in the Bulletin of the Bureau of Standards, and to some extent by the German technical press.

Both hysteresis and eddy current exponents were determined and it was found these were not a constant value for either component, the hysteresis increasing more and more rapidly as the density increased, while the eddy current decreased but to a lesser extent. The average values found are shown in the curves Fig. 1. In transformers, the decreasing eddy current loss does not materially offset the increasing hysteresis from the fact that the eddy current loss in thin sheets is such a small proportion of the total.

Fig. 2 is given to show the relation between two curves, the upper one of which is plotted using the old ordinary steel exponents and the lower curve being plotted using the exponents shown in Fig. 1, assuming the same values at 10,000 B.

The values are based on tests made on 0.014-in. sheet steel obtained from several steel makers in this country and abroad.

It is interesting to note that the hysteresis exponent in the neighborhood of 16,000 B is more than double the old value as used for ordinary steel.

A paper presented at the Pittsfield-Schenectady mid-winter convention of the American Institute of Electrical Engineers, February 14, 1911.

COMMERCIAL PROBLEMS OF TRANSFORMER DESIGN

BY H. R. WILSON

One of the most important problems confronting a designing engineer is the compromise between the design which, in his opinion, is best but too expensive for competition, and the design which can be built to barely meet guarantees and which can be sold for the lowest possible price. The designing engineer is at times compelled to cater to the idiosyncrasies of certain customers, whose special requirements, experience has proved, are unnecessary and detrimental to good construction, but which will be furnished by competitors who are less conscientious in this respect.

It is doubtful whether any line of apparatus is subject to such wide variation in requirements as transformers. Capacity, voltage (both primary and secondary), taps, heating, overloads, efficiency, regulation and overall dimensions must all be taken into consideration, and the best balance obtained, so that the design will conform to the requirements of the majority of customers.

For a line of transformers varying in capacity from 100 kw. to 4000 or 5000 kw., and in voltage from 2200 volts to 110,000 volts, the best solution of the above problems is not an easy one.

If it were possible to treat each transformer as an individual unit, the difficult problem of standardization would be eliminated, but for extensive production, this is not permissible. The standardization of parts for a line of transformers covering a wide range in capacity and voltage, demands a large number of special tools, patterns, dies, etc., the cost of which is a big item, and in order to keep down this initial cost, the number of pat-

terns, dies and tools must be reduced to the minimum, consistent with economical production. On the other hand, standardization has an important bearing on delivery; the greater the number of different parts which can be carried in stock, the shorter will be the time necessary for the production of the apparatus.

The principal transformer parts which may be standardized are: the case, punchings and size of copper strip.

Should a line of round tanks running from 3 ft. (0.91 m.) to 8 ft. (2.4 m.) diameter, vary in steps of 2 in. (5 cm.) or should the gradient be 2 ft. (61 cm.)? The former figure is obviously too small and the latter too large, but where should the line be drawn? If a line of dies for punching laminations is to be established, what will be the minimum number that can be used without sacrificing too much of the wire space on intermediate sizes? The carrying of a large stock of drawn copper necessitates the investment of much capital and consequently considerable importance should be attached to the selection of strips, in order to avoid carrying in stock, a large number of sizes for which there is very little call and which may be on hand for several years. On the other hand, too small a number of strips may mean, in many cases, the use of a larger size strip than would answer the purpose.

Another question which has been frequently discussed, is the maximum economical capacity gradient for small transformers which are to be carried in stock. Shall the standard sizes under 5 kw. be 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 kw. or will half of this number serve the purpose?

The importance attached to operating data is sometimes a handicap in a good design. Consider the question of efficiencies in its components of core loss and copper loss. Assuming a predetermined number of turns of required cross-section, the size of the wire space or window depends upon the amount of insulation used, and the relatively small amount of space required for the copper compared with that taken up by the insulation (especially in high voltage units), is apt to be surprising. The latter frequently requires from three to fifteen times as much room as the former. It will therefore readily be seen that a reduction in the insulation factor of safety, will give a reduction in core loss and that a low core loss obtained in this manner may easily deceive a prospective customer who cannot be expected to be acquainted in detail with the strength of the various insulating materials and methods of using the same.

The relation of efficiency and cost must also receive due consideration, and a choice between the least expensive, low efficiency design and the more costly high efficiency design must be made. The low cost of power development calls for the former and the latter is more advantageous where the saving resultant from a reduction in losses overcomes the interest on the first cost of installation.

A much discussed subject has been the relative proportion of overall height to floor space, especially for transformers of 500 kw. and above. A certain station layout has plenty of available floor space, but demands a transformer of limited height, while, on the other hand, another station is crowded for floor space but has head room more than necessary. For a station situated in large cities where land is valuable, the unit with small floor space seems to be better suited, while a station located in less valuable territory allows the reverse conditions. These local conditions must all be considered when laying out a line of parts which will be best adaptable for fulfilling the various requirements.

Let us consider, however, a situation where neither overall dimension is limited. What relation of height to floor space for a round or square case, will be most suitable for the average station? Shall the proportion of height over cap to floor space be 1.5: 1, or 2.5: 1, *i.e.*, will over all dimensions of say 5 ft. (1.5 m.) diameter by 7.5 ft. (2.2 m.) high be better than 4 ft. (1.2 m.) diameter by 10 ft. (3 m.) high? It would be very interesting to know if the majority of customers have a preference for small floor space and considerable height, or greater floor space and less height.

A finished outside appearance is desirable in all apparatus, but the influence of such appearance in selling a transformer is a debatable question. Is it desirable to expend the additional money necessary to obtain this finished article, or will less paint and a rough surface be fully as acceptable? Shall the same care be given to the internal parts or will rougher work pass unnoticed? If transportation facilities allow the shipment of a transformer assembled in the case, the unit is very apt to be placed in service without investigation of the inside construction, and consequently the extra care and finish pass unnoticed, at least until revealed by a general investigation.

Until the past few years power transformers were designed with a comparatively low reactance, about 2 per cent or 3 per

cent, and, as the $I R$ drop per cent decreases as the capacity increases, better regulation was obtained on the larger size units. Later experience has proven that the higher the reactance, the greater is the ability of the transformer to withstanding short circuits. It is therefore desirable to have high reactance in transformers of large capacity; especially where the total power behind the transformer is many times the capacity of the transformer bank. The result of increasing the reactance as the capacity increases, is that the regulation on loads of low power factor is considerably poorer for the larger size units than it is for those of smaller capacity. This is not however objectionable, because on large power transformers there is usually no need for good regulation.

As the modern grades of steel are practically non-aging, the tendency has been to run up the density, thereby obtaining a considerable reduction in both the amount of iron and copper; the size of the core decreasing in proportion to the increase in density and the weight of copper in proportion to the reduction in the mean length of turn. If the cost of the copper and iron is about equally divided, and a decrease of 10 per cent in density gives an increase of 10 per cent in the amount of steel, and about 4 per cent in the amount of copper, the total increase will be 7 per cent.

The principal disadvantage of a high density is the large increase in magnetizing current and core loss when operating under over-voltage conditions, *i.e.*, with a density of 50,000 lines per sq. in. (8000 per sq. cm.) for normal voltage, the per cent increase in magnetizing current and core loss when operating at 10 per cent over-voltage, is not nearly as great as will be the case when the density at normal voltage is 80,000 to 90,000 lines per sq. in. (12,400 to 15,500 per sq. cm.). The purchaser, who is apt to operate his lines above the normal rated voltage will do well to consider this question when ordering transformers.

The manner in which transformers are rated and guarantees made when operation is to be at power-factor loads, may be misleading to a customer who is not familiar with transformer design. A transformer may be required to deliver a specified number of kilowatts at a low power-factor, but through a misunderstanding between the manufacturer and the purchaser, a unit of the same numerical capacity rated on a kilovolt-ampere basis may be furnished instead of one rated on a kilowatt basis at the power-factor on which it is to operate. Now that

the practice of rating transformers on a kilovolt ampere basis has been standardized, misunderstandings of the above sort should be eliminated.

The A. I. E. E. rules state that the temperature rise of a transformer should be based on the temperature of the surrounding air. The cooling medium for oil-insulated self-cooled and for air-blast transformers is the surrounding air, but for oil insulated, water-cooled units the cooling medium is water, and it is only logical to consider the temperature rise above that of the ingoing water and illogical to refer to the temperature of the room. The purchaser of this type of transformer who specifies that the temperature rise shall be based on the temperature of the surrounding air is very apt to receive a unit having 10 deg. cent. higher heating than if he had stated that the temperature rise should be above the ingoing water, *i.e.*, for example, a guarantee to the effect that the temperature rise shall not exceed 40 deg. cent. above the temperature of the surrounding air at 25 deg. cent. with the ingoing water at 15 deg. cent. is in reality a unit having a temperature rise of 50 deg. above the water at 15 deg. cent., and consequently is a 10 deg. cent. hotter transformer than if the guarantee was 40 deg. cent. above the cooling medium, which is the water at 15 deg. cent.

The engineering and commercial conditions are so vitally related, that all phases of the situation must be considered from both points of view, and therefore the best general design of a line of transformers is the one which contains no features which are commercially detrimental, and yet will satisfactorily fulfill the requirements which will be demanded in actual service.

Discussion on "High-Tension Testing of Insulating Materials," "Hysteresis and Eddy Current Exponents for Silicon Steel," "Commercial Problems of Transformer Design," Schenectady, February 14, 1911.

C. P. Steinmetz: Mr. Hendricks' paper on "High Tension Testing of Insulating Materials" is not simply a paper, but rather a compendium of our knowledge of the characteristics of insulating materials, the methods of testing, the difficulties met, and the errors to be guarded against, and how these errors may be avoided and reliable results secured.

With the rapid development of the electrical industry in the last ten years we have advanced to higher and higher voltages, and thereby the characteristics of the insulating materials have become of increasing importance, so that probably the insulations of our electrical apparatus constitute the most important materials which enter into the construction. This has been recognized by the Institute, more particularly by its Standardization Committee, and if we compare the first report of 1897, in which we find only a short paragraph dealing with high voltage tests, with a later report, that of 1907, we find in the latter quite an explicit discussion on the methods of testing, the different precautions and safeguards to be employed, on the use of the voltmeter and the use of the spark gap, etc. Nevertheless, even the 1907 report is already somewhat antiquated, and at least those engineers who have to deal with high voltage measurements, feel that the specifications of the Institute might be revised, and therefore a motion may be advisable to refer this paper to the Board of Directors for recommendation to the Standardizing Committee in studying and further investigating the methods of high voltage testing.

There are a number of important questions raised in this paper, and among them is the question of the spark gap. Theoretically the spark gap is the ideal and only correct method of measuring disruptive strength, as it measures the strain on the apparatus tested, by comparison with the strain on the standard material, the air, under standard conditions of experiment, the spark gap between needles under specified conditions. The great difficulty is in securing standard conditions, and herein lies most of the difficulty met in the spark gap method. When this method was standardized, we had no knowledge of the effect of transient voltages, on the difference in action of one dielectric and another dielectric, with different times of the application of voltage, which means that one spark gap may be equivalent to a testing material for one amount of energy, and a different spark gap for a larger or a lesser amount of energy, so that the entire field of transient voltages enters as a fundamental factor and indeed, as the most disturbing cause in the use of the spark gap. Nevertheless, theoretically the spark gap is

the most correct method, and it therefore requires further investigation, to see how we can guard against possible errors.

The voltmeter, after all, does not measure the disruptive strain, but it measures the effective value of the voltage, from which we can calculate the maximum value, and thereby the dielectric strain. This calculation is based on a knowledge of the wave shape of the voltage. It requires a sine wave generator. Practically all modern alternating current generators give electromotive force waves which are so nearly sine waves that the error in a high voltage test made by the use of such a voltage wave on the test piece, would be negligible. But it is not the shape of the voltage wave at the generator which is the source of trouble, but the great difficulty is to get the same wave at the testing piece. There intervenes the step-up transformer, carrying a great leading current full of higher harmonics, the transient effects of its capacity, etc., and herein lies the great difficulty with the voltmeter measurements, but as the author has shown in the paper, by using the voltmeter as close as possible to the test piece, this difficulty can be largely overcome.

There still remains the effect of transient phenomena, and one of the important results of this paper is, that the spark gap which measures the maximum voltage does not eliminate the danger of the error caused by transient or momentary voltage peaks, because there enters the time element, which is different with different shapes of spark gaps; is different with liquids, such as oils, and different again with solid insulating materials. From the investigations of the last years, this entire field seems to be thrown open again for further consideration, and in the recognition of this lies one of the most important features of this paper.

With the rapid increase of operating voltages, and the increasing demands for reliability of operation, the study of insulating materials has enormously increased in importance.

Henry Pikler: The papers of this afternoon deal with subjects which are interesting chiefly to the manufacturing and designing engineer. The few remarks I intend to make in connection with these papers are from such an engineer.

The subject of the first two papers, one by A. B. Hendricks, Jr., and the other by W. J. Wooldridge, is properties of material. This truly belongs in the realm of physics and should be treated by the physicist. The physical methods of investigating the properties of material are more refined and exact than the methods at the disposal of the commercial manufacturing engineer. I look at the papers presented in this light. In spite of the comparatively crude means at the disposal of the manufacturing engineer, the paper presented by Mr. Hendricks is a very valuable one not so much for the numerical data it discloses, but chiefly for the reason that it shows the means and ways which the manufacturing engineer should adopt and pursue for the purpose of obtaining reliable results.

To discuss the paper in detail, tests are given on liquids and solids. The materials entering into the construction of electrical apparatus of to-day consist of iron, copper and insulating materials. While copper and iron are not subject to deterioration under normal conditions, the insulating material deteriorates rapidly in comparison. A superficial reader of this paper is apt to get the impression that fibrous insulating materials are very important and of great value, because the paper deals with them at great length. As to the value of fibrous materials, I wish to state that I consider it unwise to rely on them entirely. The fibrous insulating material should be considered as a binder only. It is the oils and the varnishes which make the fibres really do the work. The less we rely on an insulating material of this type for the purpose of insulation, and the more on the mechanical disposition of the various parts to be insulated, the more durable will be the apparatus manufactured.

The old methods and principles of insulation I beg to be allowed to term " the ostrich policy ". The tendency was to *hide* the various parts to be insulated from each other and to wrap them up in a large mass of fibrous material like tape, paper, etc. My ideas of insulating modern electrical apparatus are as follows:

1. The proper mechanical disposition of the various parts which are to be insulated from one another. Smooth surfaces should be exposed between parts. Sharp corners and small radii should be avoided.

2. Small and uniform electrostatic capacities are to be sought for the parts to be insulated from each other.

The adoption of the first principle will result in a uniform and a low dielectric flux density between parts and every cubic inch of the insulating material between these parts will be under uniform stress, and therefore may be used most efficiently.

The adoption of the second principle will prevent the building up of a very high potential difference, between parts to be insulated which otherwise may act as highly charged condensers.

After the first two requirements have been fulfilled, the insulating proper should consist of the following:

3. The parts to be insulated from one another should be spaced at proper distances so as to present in the way of the discharge paths between the parts, either a wall of insulating material or a creeping surface of proper magnitude.

4. Extract the moisture from all fibrous material. Coat all the surfaces and fill all space with an insulating material of high dielectric strength.

It will be found that by the adoption of these principles in the method of insulating, a great deal of expensive material will be saved, and that the highest class of insulation of *lasting* qualities will be obtained.

I do not agree with Mr. Hendricks in his statement that the auxiliary winding on the testing transformer core should be used

in preference to the direct method of measuring the voltage either by a spark gap, or by other means. I consider his suggestion a fundamental error: What we want to know is the actual potential difference between parts of the apparatus under test. When we measure the voltage on the auxiliary coil of the test transformer, what are we doing? We measure the induced e.m.f. Now we know that the terminal voltage is quite different from the induced electromotive force for several reasons— As for instance, the electrostatic capacity of the testing transformer itself, the electrostatic capacity of the piece under test. All of this cannot be neglected even if the testing transformer has a very good regulation, but supposing the testing transformer *has* a very good regulation, then we might just as well go by the ratio and not use an auxiliary coil on the testing transformer at all.

I do not agree with Mr. Hendricks that a shell type transformer is better suited for the purposes of a high voltage testing transformer than a core type.

His reasons are the larger cross-section of core, and consequently the smaller number of turns in this shell type transformer. I do not see why in a core type transformer a larger section of core could not be used and consequently a smaller number of turns. Moreover, the core type transformer allows the high-tension windings to be distributed over a greater length, and consequently cut down the potential difference, the distances and the electrostatic capacity between parts. It admits of a better regulation. By cross connecting the two halves of the high tension winding, we will obtain an absolutely uniform and comparatively low potential difference between the two halves of the winding on the two legs.

The greatest value of this paper I see is that it will lead to the standardization of the properties of insulating material. This would be very useful, particularly from one point of view, that is, it will create a relation based on something standard between the purchaser and supplier of insulating materials.

As to the second paper by Mr. Wooldridge, on " Hysteresis and Eddy Current Exponents for Silicon Steel ", I noted with great interest the results published. I feel, however, that these results should be looked at with a great deal of skepticism, because this paper gives nothing else but the results of experiments. These results are quite different from the data we had on this subject in the past. There are absolutely no details of either of the methods of testing nor of the calculation given. Therefore, this paper does not admit of discussion.

The third paper presented to us is by H. R. Wilson, entitled, " Commercial Problems of Transformer Design ".

At the very outset of this paper a principle is enunciated which I consider fundamentally wrong. I cannot accept the statement that " one of the most important problems confronting a manufacturing engineer is the compromise between the design, which

in his opinion is best, but too expensive for competition, and the design which can be built to barely meet guarantees, and which can be sold for the lowest possible price." My experience teaches me, and I think that the majority of designers will agree with me, that it is a rule, almost without exception, that the most economical design is that which involves simplicity in construction. The simplest is always the best, and at the same time the cheapest. It does not follow as a necessity that if we put too much material into the apparatus that it will have the highest efficiency or that it will do the best. On the contrary, it will be found in most cases that economy in material will lead to high efficiency if the material is properly used.

I heartily agree with Mr. Wilson that "the designing engineer is at times compelled to cater to the idiosyncrasies of certain customers whose special requirements, experience has proven, are detrimental to good construction, but it will be furnished by competitors who are less conscientious in this respect." To this point I wish to add that keen business competition has led to excesses in this respect. For this reason I feel that the recommendations of the Standardization Committee of the A. I. E. E., with regard to definitions of output and guarantee, overload and heating should be more closely followed.

There is one paragraph in this paper referring to the finish or the outside appearance of apparatus. By all means a neat and good looking finish should be demanded in preference to a rough finish, for the simple reason that neglect of any one detail is apt to introduce neglect of other details, and in general is contrary to good discipline which requires care in every detail.

Ralph D. Mershon: I did not expect to discuss these papers at all, and do not feel qualified to discuss them, because I have not previously read any of them. The one by Mr. Hendricks looks extremely interesting, and I wish he had read it in full so that I might have been better qualified to take part in the discussion.

There is one point Mr. Pikler brought up, in which he took issue with Mr. Hendricks, but in which I do not agree with him. That is the possibility of getting correct voltage readings by means of a voltmeter testing coil. I think the accuracy of the results of such a coil will depend on where the coil is located. For instance, if it were practicable to wind the wire of the test coil beside the wire of the high voltage coil, we should unquestionably get on the voltmeter a measurement to all intents and purposes the voltage at the terminals of the high-tension coil. A measurement which when corrected for the ohmic drop in the high tension, would give exactly this voltage. Now it is not practicable to so wind the test coil but it is possible to so locate it as to accomplish practically the same result.

In the high voltage measurements at Telluride 1896, the transformers used were not especially wound with reference to this method of measurement, but I selected one of the coils of the transformer for use as a voltmeter coil and from this coil

obtained the voltage readings and also the voltage for the wattmeter. The facilities for checking up the accuracy of this method of voltage measurement at Telluride were not of the best, but we made a great many test readings by attaching the power transformer to the line, putting various amounts of line on so that there were different amounts of leading current, reading the voltage from the test coil of the power transformer, and at the same time reading the line voltage by means of a step down or voltmeter transformer. So far as we could determine the measurement from the test coil was an accurate one. Later, in building the transformers for the high voltage investigation at Niagara, I wanted to have a great deal more elaborate means of insuring accuracy of voltage readings. I wanted to have a number of test coils arranged with elaborate care as to location and construction in the endeavor to approximate the results of a test coil with its wire wound turn for turn alongside that of the high voltage coils. Mr. Moody assisted me in that matter. In fact the final success of the transformers was largely due to the work that he and his assistants did in the design of them. He thoroughly convinced me, by a set of rather elaborate tests, that the method he proposed for using a single test coil instead of a number, was entirely effective. It was, briefly, that of locating the test coil in a position which was a compromise between the location if the test coil were wound directly on the iron and the location if it were wound in the manner first above indicated. The tests for determining the accuracy of the test coil so located were made under various conditions of load and power factor, and I had every reason to believe that the voltage produced by the test coil was, under all conditions, practically proportional to and in phase with the voltage on the high voltage terminals of the power transformer.

William L. Puffer: Mr. Hendricks has presented the results of experiments in the course of which those of us who have attempted anything of the kind realize that he has met and overcome some pretty hard problems. Some of us have been through these troubles and know the difficulties of making high-potential measurements, and I want to go on record as saying that I believe the most accurate method of determining the voltage of such high-tension transformers is by the method of the exploring coil. A good many years ago I used a special method which I devised as a part of a high-voltage testing set at the Massachusetts Institute of Technology and which has not been referred to here this evening. The transformer was wound with the high-voltage coil in sections of approximately ratios of 1-1-2-4, etc. A 2000-volt direct-reading static voltmeter was used and the exact ratios of the various coils measured. During any measurement this method permitted the determination of a fractional part of the high voltage by a method which was affected by all of the possible reactions of the testing current.

The ratio of the voltmeter reading to the maximum was de-

termined by the contact method, the Braun tube and finally, as the instrument was developed, by the oscillograph. The generator used was a Mordey, connected to a set of transformers used as a compensator to supply a suitable voltage for the primary side of the testing set. At that time I made many experiments to see whether the voltmeter method followed the spark gap method, and I am sorry to say that I could never get two curves nearly enough alike to represent good engineering practice.

I regret I have not had time to read the paper of Mr. Hendricks as there are many interesting points I would like to take up, and I thank you for the opportunity of saying these few words.

A. S. McAllister. The author has not defined his two terms, hysteresis and eddy currents. In separating these two he has made certain assumptions, and on the basis of those assumptions has separated the measurable losses into two parts. I wish to mention what seems to me the only source of change in the so-called eddy current and to criticise the method of separation. The eddy currents are produced by voltages, the value of which depends on the flux. Therefore, if the resistance of the path through which the current flows is constant, the eddy-current loss should vary as the square of the flux, other quantities being equal. Unless the so-called law of electromagnetic phenomena is wrong, the only thing that could have changed is the resistance in the path of the eddy current. Therefore, if the author's separation is correct, after the density reached the value of 8,000 lines per square centimeter the resistance increased, and hence the so-called change in eddy current loss if there was a change in this loss, was produced by a change in the temperature. Thus such a change is not inherent in silicon steel, except in so far as the change in temperature may change the resistance. This fact would seem, possibly, to be the explanation of the change. The change, however, is larger than one would expect from such a source, and I personally believe that the major portion of the change attributed to eddy current loss is due to the fact that the method employed in separating the eddy-current loss from the hysteresis loss would not bear close analysis.

L. T. Robinson: I have only a few words to say about Mr. Wooldridge's paper, they are along the line of Dr.. McAllister's remarks, but at the same time I think no matter what way you look at it there is something in his paper after all. If you proceed along the line of analyzing the paper on the basis of what is wrong with the eddy current determination, there certainly is something wrong. If you reason that because there is some error in that portion of the paper the whole thing is wrong, perhaps, that position is tenable, but to support the facts given in connection with the hysteresis exponents, this work has all been gone over in an entirely different way by others and in connection with my own work. We have been able to show by standard

hysteresis loops, determined by ballistic galvanometer readings, that the hysteresis does vary throughout the limits substantially as given in this paper, although I believe the figures in the paper were determined in another way. While I am somewhat familiar with the way in which this work was done, I will not attempt to explain how the figures were arrived at, as Mr. Wooldridge will prefer to cover that when he closes the discussion.

There is, however, one point about these eddy currents which is of great importance, and which I do not think is fully appreciated; one which should not be neglected by research engineers and physicists until it is straightened out, that is, while the production of eddy currents and the way in which they are connected to core losses is theoretically covered in a certain way, these theories must be very incomplete, and inaccurate. We know by separation at fixed densities, with varying frequencies, what has always been considered to be a legitimate method, that we do get results substantially as shown in this paper, and we also know that these results cannot be thoroughly understood until we have some more complete theory to account for the discrepancies found.

In connection with the subject of eddy losses we have another fact which does not show anything except the incomplete state of our knowledge on this point, that is, we have silicon iron referred to in this paper which has a resistivity of approximately five times that of ordinary iron. We also have numbers of tests on transformers which show the eddy losses at a given density in a similar transformer have varied about in the proportion of 1 to 2.5 or 3. On the basis of any theory which has so far been brought out, the eddy current should be a direct function of the resistivity, and until we can in some way measure what it is that goes wrong and why it is that the results are so absurdly different from what the resistivity values would indicate, we should not be satisfied. I simply take this opportunity to present this as one of the problems that ought to be of interest to the pure physicist. Of course, it is of engineering interest too, but it is of such absorbing interest that I cannot see why the physicists who are practicing research work for scientific information alone have not tackled the problem with more strength, I certainly hope that something will be done that will lead to a solution of it, and that we may get the explanation of why, as Dr. McAllister says, "things are not the same as it seems that they should be."

George F. Sever: The paper by Mr. Hendricks I consider as one of great value to those in the educational field. Professors in the different colleges and universities have been testing insulating materials with every known apparatus, either as they have built them, or else bought them from the various manufacturing companies. They have placed a great deal of dependence on the spark gap method, either that which has been developed by Dr.

Steinmetz and advocated in the Institute Standardization rules, or that recommended by Mr. Fisher, as presented at the International Electrical Congress at St. Louis. Other professors have used the ratio method, measuring the voltage on the primary and trusting that the ratio between the primary and secondary held for all loads and all conditions and have reported to their clients that the breakdown voltage on these materials had a certain value. The sizes of the test plates have been different at different laboratories, and have given different results, so that material which was tested at one place, if we were sure it had identical construction, when taken to another place would test out at a different value, so that the whole situation seems to have been and probably is to-day very chaotic. While talking with the representative of the Electrical Testing Laboratories a few days ago he stated that the results they secured with plates of different forms and sizes gave entirely different results for the breakdown of insulating materials, because the voltages may not have been measured correctly or there were some other conditions in the problem. Now, if the results of Mr. Hendricks' investigations are correct, we will have a perfectly uniform method for the measuring of voltage on high tension work, and I think his paper will lead us in that direction and a final and definite method will be available for incorporation in the Standardization Rules.

Some time ago I wanted to measure high voltages at Columbia and was able to use a condenser method. Later I found the condenser method used up to certain voltages at the works of the General Electric Company, and I want to ask Mr. Hendricks if the condenser method could not be made a standard method, using two or more condenser plates in series and measuring the drop with a static voltmeter across one or more plates, as the conditions required; there have been condenser voltmeters built, and employed successfully. I would like to hear a discussion on the possibility of using condensers in series, the plates being of small size so as not to disturb the circuit too greatly.

I would like to ask if this method which is proposed is applicable to all voltages from the lowest, say 10,000 volts, which sometimes has to be used, up to 400,000, which seems to be the typical voltage indicated in Mr. Hendricks' paper. Cannot we use some simpler method for the lower voltages, say up to 50,000? You must remember that universities which sometimes have to teach high-voltage experimentation, do not have all the necessary funds for building or purchasing high-tension apparatus. If there is any other simple method, which does not cost too much for the universities to indulge in, I as one of the Professors would like to know about it.

J. R. Craighead: The real purpose of laboratory investigation of insulating materials is to secure data which may be applied to the design of insulated apparatus. Any satisfactory method of test used in the laboratory must therefore furnish results which

are directly comparable with those obtained by tests on installed apparatus. The use of voltage as the connecting standard would be satisfactory if a statement in terms of voltage applied meant the same insulation strain in both cases; but it frequently does not. Mr. Hendricks, for instance, speaks of limiting the wave of a generator to practically a sine by using a special generator and then by not overloading the generator beyond certain limits. Now, that is usually impracticable when you come to apply it to a large installation, such as testing cables on a city circuit. There the testing outfit is usually so designed that the maximum capacity of the transformers must be used to carry simply the testing load. This means that a certain variation from a proper wave shape is unavoidable in these practical tests.

With respect to the control of the apparatus, we meet another difficulty. The control of the apparatus by the generator field would be a perfect method if it could start from zero and go up to an unlimited quantity. But it cannot. It generally must start somewhere around 50 per cent of the full voltage of the generator. That presents difficulty in practical tests of large cable systems, for the reason that when you close the main switch on a cable system you throw a heavy capacity load on the testing outfit, and in some cases the voltage of the generator at once jumps up to much more than 50 per cent of normal, and there is a first increment of such size as is dangerous to the system. To meet a condition like that, it is possible to use an induction regulator, which can be arranged to buck or boost voltage, so that with a given generator the voltage can start at zero and run through any gradation to the highest limit specified. At the same time the induction regulator has considerable exciting current and some impedance, and the result is a certain distortion of wave shape, which need not be excessive, but which must always be reckoned with. Since these distortions of voltage wave form may cause differences in the stress on the insulation without changing the indication of the voltmeter, the voltmeter is not a satisfactory primary standard to connect tests made under widely varying conditions. Such a connecting standard should be practically independent of the usual changes of voltage wave form, giving a result under all conditions which depends directly on the stress on the insulation, rather than on any special function of the voltage. Up to date this primary connecting standard is the spark gap.

The spark gap is by no means perfect. I do not need to go into its difficulties. They have been taken up; but at any rate we are measuring a length with the yard stick when we measure the insulation strength of material by comparing it with the insulation strength of a known material, that is, air. The qualities of the materials are not strictly the same, but for the present it is the best we can do, and is an effort in the right direction.

Consequently, all we can ask is that some one should provide a better standard than this, and the better standard must be

associated not with the idea of how much voltage a thing can stand, because the standing of voltage means a great many different things of different kind, but it must mean a comparison of dielectric strength with the dielectric strength of some known material and the simplest and best known material is air.

In respect to the measurement of the voltage as a secondary standard the volt coil certainly works well, but where the voltages are not too high a potential transformer may be used on the high potential side; we are then enabled to take the voltage directly where it is applied, instead of at a point back in the circuit with more or less uncertain components between. This potential transformer can be made with practically any accuracy desired.

J. L. R. Hayden: The curves on Fig. 1 of the paper on hysteresis and eddy current exponents of silicon steel are very interesting and startling.

That the Steinmetz law of hysteresis does not hold for very low densities has been shown already by Dr. Steinmetz in his original paper. A decrease of the hysteresis coefficient at high densities has been observed repeatedly. Unexpected, however, is an increase as shown in Fig. 1. Further investigations on the cause of this increase would therefore be interesting.

Questionable appears to me the curve of eddy currents. Eddy currents are induced currents and the loss by them is an $i^2 r$ loss and therefore must be proportional to the square of the voltage, and to the square of the magnetic density. An exception could occur only if the resistance changed or magnetic screening took place. With a material of such high resistance as silicon steel this is not probable.

It therefore appears probable that the eddy current losses are so small a part of the total loss as to make their determination inaccurate.

F. M. Farmer: I had a few points that I intended to mention, but most of them have been covered by other speakers. I would emphasize the point Professor Sever brought up about the electrostatic voltmeter. We have used it and consider it successful and satisfactory for moderately high voltages, up to, say, 50,000, where the conditions did not prohibit the use of an instrument measuring mean effective values. I have in mind more particularly the effect and size of the electrodes. Professor Sever has spoken of this point. We are making an investigation now, and the results will be available in the course of a few months but the indications are that the size of the electrode does have a great effect on the apparent dielectric strength of thin materials, such as cloth and paper. The first thought is that when using large sizes of electrodes the electrostatic capacity may affect the wave form. We might get a peaked wave, the maximum of which determines the puncturing value and which is not shown by a voltmeter either in the primary, a voltmeter on the exploring coil of the secondary or an electrostatic voltmeter in the secondary. If we can use small specimens where there cannot

be any question of distortion of wave, I do not see any reason why the electrostatic voltmeter would not be satisfactory.

The method involving the use of the ratio of transformation when correctly determined and a voltmeter on the low tension side is also satisfactory.

I would refer to the cup and disk device which Mr. Hendricks speaks of. I cannot see where it has any material advantages over the apparatus most of us are more or less familiar with, using spheres. I believe the sphere device is known as the Skinner apparatus. Mr. Hendricks' suggestion means the use of less oil, but that is not ordinarily of much consequence, and as regards 45,000 volt transformers, instead of 60,000 volt transformers, that does not seem to be a very important point, because if you have a transformer that is good for 45,000 volts, the chances are it is all right for 60,000 volts for testing purposes.

Another point I want to mention is the work of the Committee appointed by the American Society for Testing Materials whose object is the Standardization of Tests of Insulating Material. That Committee is endeavoring to standardize not so much the kind of tests that should be made, but the methods of making the tests. As has been mentioned this afternoon, the whole thing is in a chaotic state. One man gets certain results by his methods and another man gets something entirely different on exactly the same material. It is hoped that the efforts on the part of that Committee to get information along this line will be encouraged by the members of the Institute, and they will give their assistance as far as possible. It is certainly a very important thing, and should be helped in every way possible.

H. L. Schermerhorn: I find in Mr. Hendricks' tests that the areas are rather small. It seems to me while it is very nice to have a fine scientific research made and the results given, of the insulating materials for our electrical apparatus, what we need now is something that is practical. In these days when so many young electrical engineers are coming forward to take up engineering work, without very much shop training, or opportunity to do some of this kind of testing work, they do not have the practical knowledge to take such results and bring them down to a practical basis—what I mean by that is they could not take these figures and use them in designs without serious results. Larger areas and larger number of samples tested under longer time periods give more practical results than the small samples under short time periods. The greater number of tests give very satisfactory results, and often times startling ones to the people who deal with them. The standardization of areas is an extremely important matter, and one which I would advocate the Institute to take up, and fix a standard for, so that all investigators could follow the same definite line.

E. M. Hewlett: The paper by Mr. Hendricks is more for the laboratory test, as I understand it. We need a quick test for

the practical work of the factory, and the spark gap seems to be the most convenient test for us to use. If we could have a new curve giving us the values of the spark gap on the upper end of the curve, up around 500,000 and 700,000 volts, I think that is what we are more interested in at the present time, in connection with the oil switches, etc., so it would seem as though for establishing the values of the spark gap or resistance across the high potential, a voltmeter or oscillograph in shunt with this resistance, and the necessary ground to make the test, could be used, and in that way new values for the spark gap might be plotted.

In reference to the testing of the liquids, that is, oils, etc., while they all break, down at a certain voltage when they are dry and in proper condition, if they are tested for time, there is a great difference. That is not mentioned in the paper. We should remember that there is a great difference in liquid insulation and in solid insulation in bulk, particularly under time test.

W. J. Foster: I had in mind to say a few words regarding the potential wave of alternators. I now hesitate as it has been brought out in the discussion that you can have almost any kind of a wave when you get on the other side of the transformer. I do want, however, to compliment the author on the thoroughness with which he has prepared his paper, and his attempt to have everything perfect, beginning with the potential wave of the alternator. The pictures of alternators that he shows are as comprehensive as the life of the industry. He shows an old high periodicity single phase revolving armature smooth core machine, which, as he says, has a good potential wave, and also the very latest turbine generator type with distributed windings in the field as well as the armature.

A well designed machine has a good potential wave, approximately a sine wave. There is quite a difference in machines designed for the same uses, between one of large capacity and one of small capacity when open slots are used. This is brought about by the fact that the breadth of the slot is about the same for a given potential in the very small machine and the large machine, whereas the air gap is much greater in the large machine. The potential wave is affected by the open slot and higher harmonics corresponding to slot frequency are likely to appear provided we do not take certain precautions. There are two or three ways of securing good potential wave. Such as the proper shaping of the pole face, so as to give the sine distribution of magnetism in the air gap; and looking out for the pitch of the windings rather than to use full pitch. One of the best ways of designing machines, even a small machine, such as would be in demand for testing purposes, is to avoid making the number of slots a multiple of the number of poles, in other words, design the machine for a certain number of poles and drop out two or more. This gives a Vernier arrangement in the super position of the potential waves of the individual coils, and in that way

practically as good potential wave can be obtained as any shown by Mr. Hendricks in his paper.

Charles F. Scott: I want to speak a word for the Standardization Code. It is neither an oracle nor an encyclopedia. Many people seem to think if it does not cover everything that there is something the matter with it. There have been two uncomplimentary comments this afternoon. One of them was in the paper in regard to transformers with water cooling, and referred to the temperature specifications and outside air. The conditions are obvious. The heat will be partly carried away by the cooling water and partly by the air in contact with the outer surface, and the temperature will depend upon the temperature of the entering water and the temperature of the surrounding air. The whole matter is one for individual specifications in the case of the particular transformer and not for general specifications in the Standardization Rules. All that the latter attempts to cover are certain principles and certain general conditions. Particular cases, especially when they concern large apparatus in which competent engineers are concerned, are left to the intelligent action of such engineers.

In Mr. Hendricks' paper reference is made to the fact that the present Institute specifications prescribe a uniform insulation test for all parts of the winding of a transformer, although in certain cases, it may be known that one end of the winding or the middle point will be permanently grounded. When the present Standardization Rules were in preparation, I undertook the task of drafting a paragraph covering cases of this kind. Objection was made to it for the reason that when a transformer is built, it may not be definitely known whether it is to be used on a single phase circuit or on a three phase circuit either in star or delta connection, or whether some point may be connected to the ground. Whatever the intention may be, the transformer is liable to be used in some way other than that for which it was intended. Hence, it was found impracticable to prescribe rules which would not be quite complex and liable to misapplication and misuse. It was, therefore, decided to make the general specifications so that they would serve for all transformers and to leave special specifications to the discretion of the engineers in special cases.

The principle involved is indicated in this sentence in the Rules:

> The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases and are proposed for general adoption, except where specific reasons make a modification desirable.

C. A. Adams: I understand that the hysteresis and eddy current losses were separated in the ordinary manner by assuming that the former is proportional to the frequency and the latter to the square of the frequency. But after this separation, how were the exponents of Fig. 1 determined? Also, were the corresponding coefficients determined?

Wm. A. Del Mar (by letter): The subject of dielectric stress in the insulation surrounding a cylindrical conductor has lately given rise to considerable discussion at meetings of the Institute and elsewhere, and particular interest has been evinced in a curious phenomenon observed when dielectrics are subjected to powerful electric stresses, the dielectric acquiring temporarily some of the characteristics of a conductor without suffering any mechanical or physical damage of a permanent nature. This phenomenon was observed several years ago by Dr. E. Jona and again by Professor Alexander Russel, neither of whom offered a satisfactory explanation of it.

In order to fully grasp the significance of this phenomenon, it will be well to refresh our minds with certain well known facts and formulae relating to the quantitative expression of dielectric stresses in cables.

The following well known formula is based upon the assumption that the lines of electrostatic induction extend radially between the conductor and cable sheath and that therefore

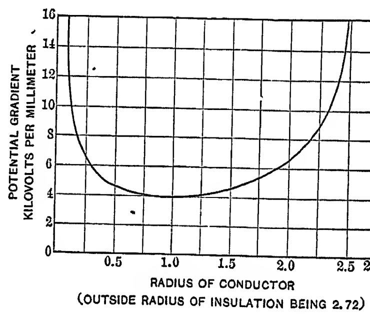


FIG. *A*

their density, or, in other words, the dielectric stress is greatest at the surface of the conductor.

$$K = \frac{V}{r \, ln \frac{R}{r}} \qquad (1)$$

where K = the dielectric stress at the surface of the conductor when the volts between wire and sheath equal V.

R = outer radius of insulation.

r = radius of conductor.

This equation is plotted as a curve in Fig. *A*. Its physical interpretation was discussed by the present writer after the paper on "Potential Stresses in Dielectrics", by H. S. Osborne in PROCEEDINGS A. I. E. E., December, 1910. Let it suffice to repeat that in the case of cables in which R/r is greater than 2.72, if the conductor were to grow in diameter, the dielectric

stress at its surface would decrease until its diameter became $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would increase. If instead of the conductor growing in diameter, the dielectric at its surface were to break down, the effect would be the same. The stress in the uninjured dielectric where it meets the injured part would decrease until the diameter of the injured part equalled $\frac{1}{2.72}$ of the outside diameter of the insulation, after which the stress would increase. If, therefore, the applied voltage is just sufficient to break down the layer of insulation nearest the conductor, the next layers of insulation will not necessarily break down, as the virtual increase of conductor diameter, due to the breakdown of the inner layers, will have eased the stress to a safe value. Hence, as pointed out by Alex. Russel, a partial internal disintegration of dielectric should be possible in such a cable without a complete puncture.†

An interesting contribution to the discussion referred to above, was that of Mr. W. I. Middleton, who pointed out that according to equation (**1**), the outside diameter of the insulation may be made a constant entirely independent of the size of the conductor and dependent only upon the applied voltage. Thus, referring to equation (**1**), assume that $\frac{R}{r}=2.72$ so that $r=\frac{R}{2.72}$ and $ln\ \frac{R}{r}$ becomes unity. Then

$$K=\frac{2.72\ V}{R},\ \text{or}\ R=\frac{2.72\ V}{K} \qquad (2)$$

This equation was shown by Mr. Middleton and Mr. Henry A. Morss to be amply confirmed by a great number of tests, so that it is in no sense theoretical or speculative; but it will be observed that its derivation from equation (**1**) depends upon the assumption that the inner layers of insulation are in some way broken down without injury to the outer layers. Mr. Middleton, however, said that " as far as Professor Russel's hypothesis that the dielectric near the conductor breaks down and becomes charred, is concerned, I do not believe it. In eight years in the testing room of a cable factory, I have never seen a cable that has shown mechanical change due to excess voltage in either rubber or cambric insulation ".

†Prof. Russel's conclusions have apparently been accepted by one of our leading manufacturers, upon whose specifications appears the following sentence: " Higher voltages, although not necessarily causing a breakdown of the insulation, are apt to *strain* it."

Other careful experimenters have said that they have never known rubber to break down mechanically or physically under high dielectric stress when the conditions of the test have precluded a complete rupture.

We are thus led to the anomaly that a formula is arrived at by theory and found correct by tests and then the theory upon which it is based, is apparently denied and contradicted.

The object of this contribution is to suggest an explanation of this apparent inconsistency.

A large number of chemical analyses of rubber compounds shows that there is always a certain amount of moisture present, the amount usually varying between one-quarter and one-half per cent by weight, which is equivalent to between one-half and one per cent by bulk. This amount is doubtless increased during the usual twelve or twenty-four hour immersion in water for testing purposes, so that a rubber compound may be regarded as permeated throughout its mass with minute particles of moisture. This moisture has a very perceptible effect upon the resistance of the compound as measured by the ordinary galvanometer method after electrification for one minute, it being the practice of many manufacturers to boost the resistance by placing the compound in a drying oven for a few hours before testing. This commercial drying process often doubles the resistance of the insulation, showing that moisture is present in sufficient quantities to radically affect its electrical properties. The specific resistance, however, is not the only electrical property affected by the presence of moisture. Rubber compounds usually have a specific capacity of about 2.5, while that of water is about 80, which is 32 times as great.* The significance of this, lies in the fact that when a dielectric of high specific capacity is placed in a field of electric force traversing a medium of lower specific capacity, the tubes of force tend to run through the foreign dielectric, because by so doing the potential energy of the system is decreased. If this dielectric is free to move, it can further decrease the energy by moving from its original position to one where the tubes are more thickly congregated, because the more tubes which pass through the dielectric, the greater the decrease in potential energy. The foreign dielectric will therefore be urged towards the part of the field where the tubes of force are the densest. In the case of the radial field between a cylindrical wire and a concentric sheath, the moisture in the dielectric will therefore be impelled towards the wire, with the result that the inner part of the insulation will become more impregnated with moisture than the outer, the particles of moisture ranging themselves about the core in much the same way that iron filings range themselves near the poles of a magnet. In order to study the effect of this condition, it will be well to refresh our memories about a well known experiment originated

*If permeated with electrolyte the specific capacity of water will be much greater than 80.

by Nicola Tesla. If two large conductors *A* and *B* (Fig. *B*) are separated by air, and the maximum possible difference of potentials set up between them, the potential gradient will be approximately represented by a straight line such as *D*. If, however, a piece of glass *C*, be introduced between *A* and *B*, the air will be electrically ruptured. The well known explanation of this phenomenon is, that the glass having a higher specific capacity than air takes a correspondingly lower potential gradient, thereby increasing the gradient in air beyond the rupture point as shown by curve *E*. The specific capacity of glass is about eight times that of air; if it were thirty-two times as great, the potential gradient would be as shown by curve *F*.

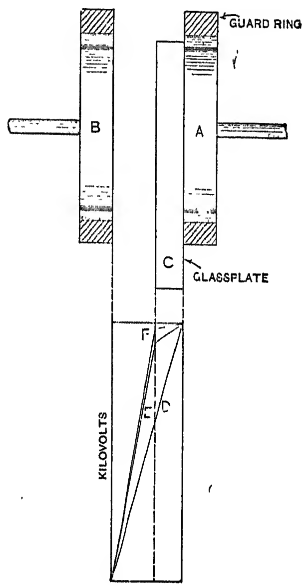


FIG. *B*

In other words the potential of the conductor *A* would virtually be carried to the outer edge of the glass.

This is possibly what happens in the moisture impregnated cable insulation. The potential gradient along the zones of moisture is practically zero, carrying the potential of the wire far into the insulation. The moisture is, however, not continuous, so that the equipotential lines are not concentric with the wire, but consist of a series of attenuated peaks having their minima at the surface of the wire and their maxima deep in the insulation. The inner insulation would therefore be unable to support a potential gradient, as shown by Mr. Middleton's tests, and yet would show no sign of internal breakdown, thus giving rise to the anomaly which has been fruitful of so much discussion.

If this theory is correct, the cable should show practically no increase of capacity when stressed to near the rupture point, as would be the case if the inner layers had been reduced to a conducting state, for the capacity is a measure of the number of tubes of force between the wire and sheath and this will not have materially increased, owing to the small proportion of the total dielectric which is occupied by water particles. That the capacity actually does not materially increase, was shown by careful tests made by Dr. Jona and others; and their results have been confirmed in the course of commercial testing by measurements of the charging current prior to breakdown.* Another requirement of the theory is that the occluded moisture must be free to move within the insulation. That such is the case, is known to those familiar with the phenomenon of water entering negative mains by endosmose,† and is also deducible from the rapidity with which moisture may be removed by means of a drying oven. This theory may also explain the well known fact, mentioned by Mr. Hendricks, that the dielectric strength of insulation such as rubber compound, is greater when electrified for a short time, than when the electrification is prolonged, because at first all of the rubber carries the potential gradient, while after the moisture particles have congregated, almost the entire gradient will have to be carried by the outer layers of insulation. Furthermore, after a certain time, the dielectric strength shows no further decrease, which is explained by the fact that all the moisture finally reaches a position of equilibrium, corresponding to the minimum potential energy. That a minute proportion of moisture has the effect of reducing dielectric strength to a remarkable degree, is well shown by Mr. Hendrick's curve for transformer oil, Fig. 21. The percentage by bulk of water in rubber insulation has been stated to be from one-half to one per cent. The effect of one-tenth of one per cent of moisture in transformer oil, is to reduce its dielectric strength to about one-seventh of its value when dry, and what is even more significant is that the greater part of this reduction is due to less than one part of water in 10,000, the further addition of water having but little effect. Analogy would lead one to suppose that a correspondingly minute proportion of water would effectually alter the dielectric strength of rubber and that additional water would have little or no effect.

It might be objected that this theory does not explain the Middleton phenomenon because the outer limit of the displaced water particles does not necessarily correspond to the radius $r=\frac{R}{2.72}$ and therefore the effect of the water particles would be to give an indeterminate reduction of the effective thickness of insulation. This objection would be fatal were it not for the

*Alex. Russel, November 7, 1907. Journal I. E. E. (London), Vol. 40.
†Journal I. E. E. (London), August 1908, p. 455.

following fact. By reference to Fig. A it will be observed that the curve A is almost flat for about one-third of its span. In other words, if the insulation be supposed to be divided into three concentric layers of equal thickness, and the outer limit of the moisture particles is anywhere within the middle layer, their effect in reducing the effective thickness of insulation would be practically the same as if they extended exactly to the radius $\frac{B}{2.72}$.

A corollary to be deduced from this is that rubber insulation may be susceptible of internal destruction without puncture, if perfectly dry, but the presence of moisture, even in minute quantities will prevent this action by affording a natural "grading" of the insulation.

The reader is again reminded that all this is mere theory and that experimental work is required to prove or disprove it. It is to be hoped that someone who is well equipped for the work, will undertake the required experiments, as the theory has a practical bearing on the manufacture and use of cables.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, Feb. 15, 1911

DESIGN, CONSTRUCTION AND TEST OF AN ARTIFICIAL TRANSMISSION LINE

BY J. H. CUNNINGHAM

A little over a year ago Dr. Steinmetz suggested the construction of an artificial transmission line or "slow-speed conductor" in the Electrical Laboratory at Union College. It was proposed to duplicate or reproduce as nearly as possible the conditions of a high-voltage long-distance transmission line in the laboratory in such a way that the various phenomena connected with a line of this sort might easily be investigated. It was not desired particularly to study the effects of very high voltage but rather to investigate and study the various transient and other phenomena in connection with switching, sudden change of load, etc.

DESIGN

Various methods of reproducing the conditions of a transmission line were suggested and the most satisfactory method consisted of winding wire of suitable diameter on glass tubes or cylinders and lining the cylinders with tin foil. In this way, by selecting the proper diameter of wire and proper diameter of tube, any relation between resistance, inductance and capacity could be obtained. Calculations were therefore made to find the diameter of wire and size of tube that would give the most economical design.

It was at first intended that each unit or cylinder should have constants equivalent to about one mile (1.6 km.) of line such as No. 0 B. & S. gauge conductors spaced five feet (1.5 m.) apart. It was soon found however that to obtain sufficient electrostatic capacity a cylinder of very large diameter (about 10 in., 25.4 cm.) would be required, and the cost of such cylinders

was found to be expensive. In view of this fact it seemed advisable to use the half mile instead of the mile as unit. Each unit should have therefore approximately the following constants:

Resistance, 0.25 ohms; inductance, 0.001 henrys; capacity, 0.007 m.f.

The formula used in computing the inductance is as follows:

$$L = \frac{4\,\pi^2\,r^2\,n^2}{l \times 10^9} \times 2.54$$

where L = inductance in henrys.
r = radius of winding in inches.
n = number of turns.
l = length of coil in inches.

The formula used for computing the capacity is as follows:

$$C = 4.54 \times \frac{l\,r\,k}{2d \times 9 \times 10^5}$$

where l = length of tube.
r = radius of tube.
d = thickness of glass.
k = specific inductive capacity of glass.

Using the above formula various combinations of length of tube, diameter of tube, and number of turns and diameter of wire which would give the proper constants were worked out. Prices were then obtained on various sizes of glass cylinders and it was finally decided that the most practicable design called for a cylinder six inches (15 cm.) in diameter, $\frac{1}{8}$ in. (3.1 mm.) thick, $4\frac{1}{2}$ ft. (1.36 m.) long wound with 240 turns of No. 8 B. & S. gauge copper wire.

Substituting these values in the above formula the following constants are obtained. Three inches on each end of tube are left free of winding.

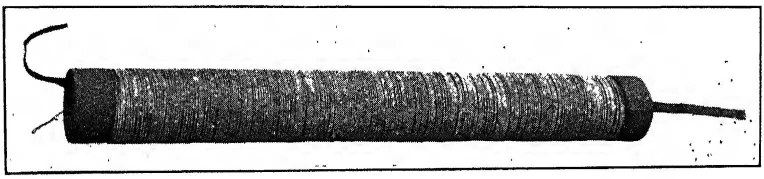
$$L = \frac{4\,\pi^2 \times 3^2 \times 240^2 \times 2.54}{48 \times 10^9} = 0.00104 \text{ henrys}$$

$$C = \frac{2.54 \times 48 \times 3 \times 4.5 \times 8}{2 \times 9 \times 10^5} = 0.00748 \times 10^{-6} \text{ farads}$$

The value used for k is 4.5. This factor is rather indefinite, different authorities giving values which vary from 3 to 10. The value 4.5 was taken as an average value and the results of experiments on the line show that this value is probably too high.

The resistance of 240 turns of No. 8 B. & S. gauge wire is 0.24 ohms, at 20 deg. cent. This is the resistance of one-half mile (0.8 km.) of conductor between No. 0 and No. 00 gauge copper wire. With the above design each unit should be equivalent to one-half mile (0.8 km.) of No. 00 gauge wire spaced five to six feet (1.5 to 1.8 m.) apart.

In order to hold the tubes in as compact, safe, and at the same time accessible form as possible, suitable racks were designed. As each tube when complete weighs about 40 pounds, a rack of fairly heavy construction was required. Because of the limited floor space the racks had to be built as high as the ceiling would permit. Each rack, as designed, carried 100 tubes in 10 rows



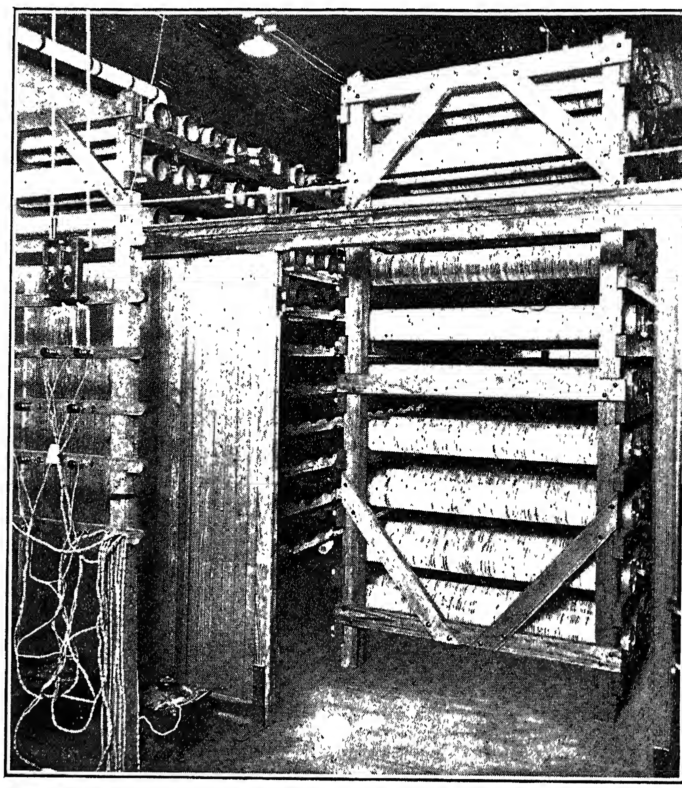
A single unit

of 10 tubes each. Their approximate dimensions are 9 ft. (2.7 m.) long by 8 ft. (2.4 m.) high by 4½ ft. (1.3 m.) wide. These racks have proved entirely satisfactory.

Construction

The wire was placed on the glass tubes in the following manner. It was first attempted to wind the wire directly on the tubes. This was done by passing a rod threaded at both ends through the tube and clamping it in place in the centre of the tube by means of blocks at each end. Because of the uneven manner in which the ends of the tubes were cut off this method of clamping set up stresses in the glass which broke the tubes. Felt pads were tried to distribute the pressure more evenly but were not found very satisfactory. This method was finally abandoned. Instead of winding the wire directly on the glass tube it was first wound on a wooden form constructed for this purpose. This form consisted of a cylinder 6¼ in. (16.8 cm.) in diameter and

5 ft. (1.5 m.) long mounted on bearings about 5 ft. (1.5 m.) from the floor. A pulley was attached to one end of the cylinder and belted to a shunt motor. There were 230 turns (equivalent to 240 turns on the glass tubes) wound on the forms. The coils were then loosened, slipped off the wooden cylinder, and were then ready for mounting on the glass cylinders. This method proved entirely satisfactory.



A portion of the line

End connections were made by means of a copper strap one inch (2.5 cm.) by 0.025 in. (0.63 mm.) by about one foot (30.5 cm.) long. These strips were soldered to the last turn and formed very convenient terminals.

The solenoids of wire after being removed from the wooden form were mounted on the glass tubes. The loosened coil was slipped over the tube. The copper strap at one end of the wire

was then tightly fastened to the tube by means of several layers of one inch (2.5 cm.) by 0.007 in. (0.18 mm.) linen tape, which was afterward thoroughly varnished. The wire was then distributed as evenly as possible over the entire tube, tightened by turning the wire, and made fast at the other end by taping.

The tin-foil lining was placed in the tubes in the following manner. Sheets of raw-hide fibre of 40 mil thickness were cut in strips 54 by 17.5 in. (137 by 44.4 cm.). The tin-foil was then pasted on these sheets of fibre by means of a coating of varnish. A small margin was allowed at each end also longitudinally to prevent the foil acting as a short circuited secondary. Transverse slits were cut at intervals of 6 in., alternately half way across the sheet, to prevent eddy currents. Small copper leads were then soldered at one end of the tin-foil sheet. The chief difficulty in soldering is that if the iron is too hot the tin-foil will be melted. By proper care however a good joint can be made. The sheets of tin-foil were then placed in the glass tubes and the leads connected together by soldering them to a bus. This consisted of No. 8 B. & S. gauge bare copper wire attached to the frame of the rack by porcelain insulators.

The next difficulty was to keep the tin-foil pressed out firmly against the glass tubes. The fibre did not prove springy enough to adapt itself completely to the form of the tube. It was decided to use expansion rings to press the fibre more firmly against the glass. Hard drawn copper wire was first tried for this purpose but did not prove stiff enough, and also showed a tendency to slip longitudinally. Phosphor bronze strips 5/16 in. (7.9 mm.) by 30 mils and $\frac{1}{2}$ in. (12.7 mm.) by 30 mils were finally used. These rings proved quite satisfactory; three were used per tube. By their use the electrostatic capacity of the tubes was considerably increased. Care must be taken in placing the rings in the tubes not to crack the glass. One hundred and fifty tubes were constructed in this way during the spring of 1910, the work being done by Messrs. Becker and Grover, seniors in the Electrical Engineering Department of the University. After some preliminary testing it was decided to continue with the construction and at present the line consists of 400 cylinders.

The line is represented diagrammatically by Fig. 1.

The diagram shows the method of connecting the units together and with sufficient number of units a line of any length could be produced.

Constants of Line

The complete line has the following constants:

Capacity 1.135 microfarads. Inductance 0.3944 henrys. Resistance 93.6 ohms.

The capacity was measured as shown in Fig. 2.

As seen by the diagram, the potentiometer method was used to eliminate harmonics. Also, the tubes were connected in multiple so as to measure the true capacity and not the charging current of the line.

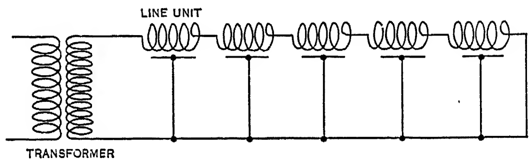


Fig. 1

From the above constants the equivalent length of the line is determined as follows:

In a circuit of distributed capacity and inductance the resonance frequency or natural period is expressed by

$$f = \frac{1}{4\sqrt{L\,C}}$$

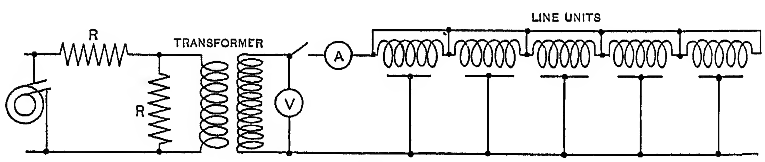


Fig. 2

where L = total inductance in henrys.
C = total capacity in farads.

$$f = \frac{1}{4\sqrt{0.394 \times 1.135 \times 10^{-6}}}$$

$$= 360 \text{ cycles.}$$

Since the propagation of an electric wave is at the same rate as the velocity of light or about 186,000 miles (299,338 km.),

per second it follows that the natural period of a line may be represented by the expression

$$f = \frac{186{,}000}{4\,l}$$

where $l =$ length of line in miles.

Substituting for f its value, 360 cycles, gives as the equivalent length of line 130 miles (209 km.).

Since the total resistance of the line is 93.6 ohms the resistance per mile of the equivalent conductor lies between that of a No. 1 and No. 2 B. & S. gauge wire. The artificial line is thus equivalent to 130 miles (209 km.) of No. 1 (approximately) B. & S. gauge wire.

The capacity of the line is considerably less than that expected from the design. This is due to several causes. In the first place the tubes were assumed to be of the uniform thickness of $\frac{1}{8}$ in. (3.1 mm.). The tubes actually varied anywhere from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. or $\frac{3}{8}$ in. (3.1 mm. to 6.3 mm. or 9.5 mm.). in thickness. This of course greatly reduced the electrostatic capacity. In the design it was assumed that the tin-foil pressed tightly against the glass. In practice it was found impossible to make it do so, there being more or less air space between the tin-foil and glass. Again the specific inductive capacity used in the design may have been too high. If some better means of lining the tubes with the tin-foil can be devised the capacity of the line will be greatly increased.

A great amount of trouble has been caused by the breaking of tubes. After being completed and placed on the racks they would crack with no apparent cause. This breakage was large at first but gradually became less and it now seems that those which are going to break are eliminated.

A summary of the lines is as follows:

Number of tubes in line............	400
Capacity of line...................	1.135×10^{-6} farads.
Inductance........................	0.3944 henrys.
Resistance of line.................	93.6 ohms.
Natural period $\frac{1}{4\sqrt{L\,C}}$............	360 cycles.
Equivalent length of line $\frac{186000}{4\,f}$....	130 miles (209 km.)
Equivalent size of conductor........	Between 1 and 2 B. & S.

Tests on Line

The following records show the results of some of the tests that have been made on the line. Three classes of tests are shown; *a*, throwing voltage on the line, *b*, opening the line, and, *c*, switching line on line. The work was all done with about two thousand volts on the line, power being taken from the city lighting circuit.

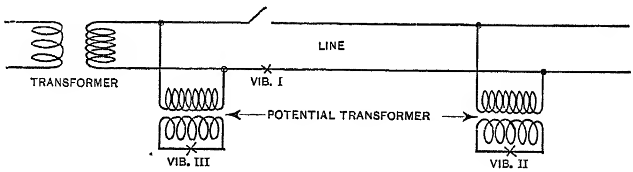


Fig. 3

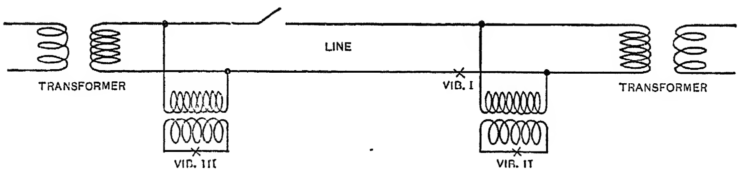


Fig. 4

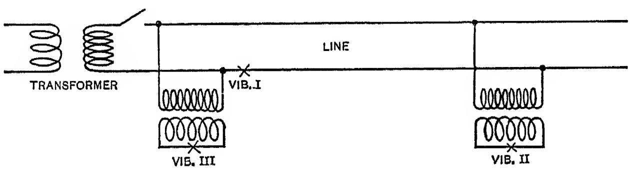


Fig. 5

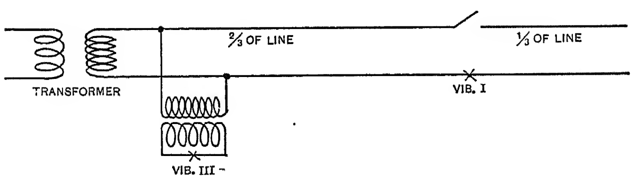
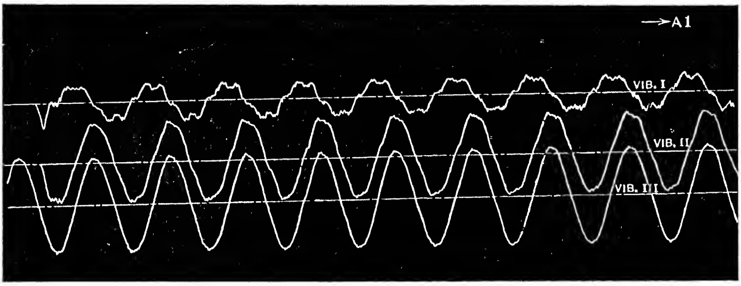


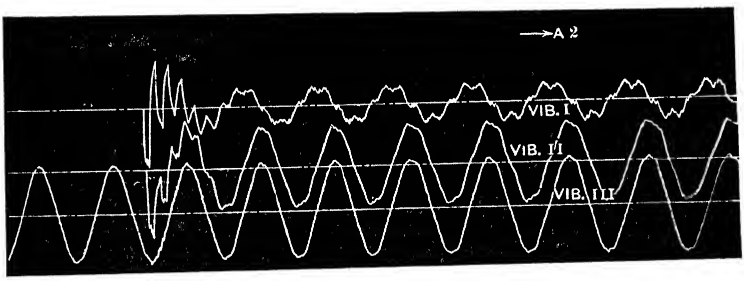
Fig. 6

a. Closing Line. The conditions under which these records were taken are shown by Fig. 3. Voltage was thrown on the line which was open except for a 50-watt, 50 to 1 potential transformer connected across the receiver end. The record shows the voltage at the generator end, the voltage at the receiver end, and the current. In all the records vibrator I is current, vibrator II voltage at receiver end of line, and vibrator III voltage at the generator end of line.

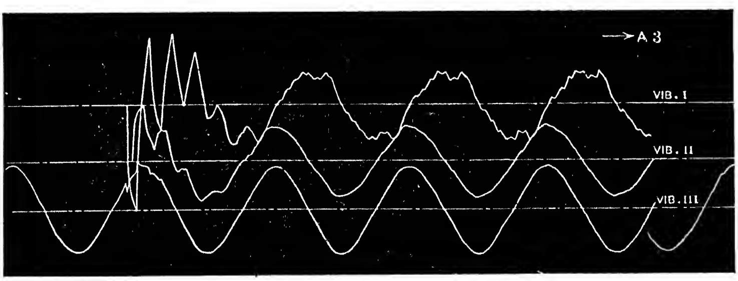
In record a-1 the line was closed near the zero value of voltage, and very little surge of current and voltage resulted. In records a-2 and a-3 the line was closed near the maximum point of the voltage wave, and surges of considerable magnitude both



Record $A1$



Record $A2$

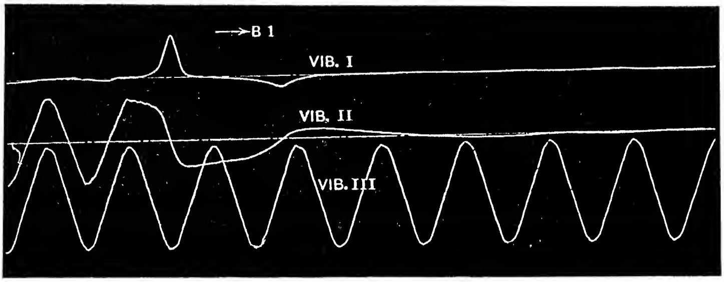


Record $A3$

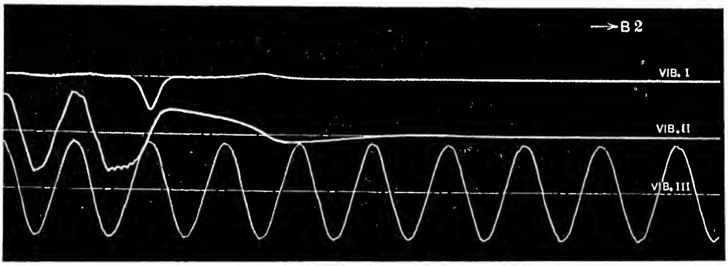
of current and voltage at receiver end result. The rise of voltage at the end of the line with the first rush of current is very noticeable.

b. Opening Line. These records were taken under the con-

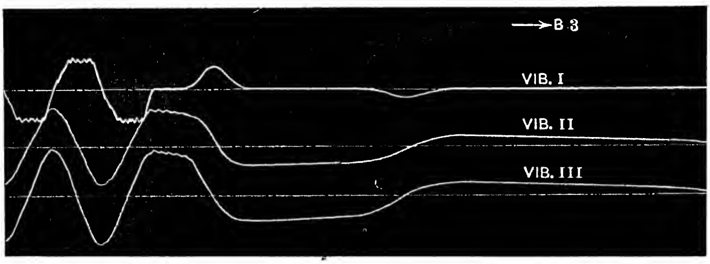
ditions shown in Fig. 4 and Fig. 5. In records *b*-1 and *b*-2 the line was opened at the generator end while feeding into a transformer at the receiver end. The current was measured at the receiver end of the line. When disconnecting switch is open the



Record *B*1



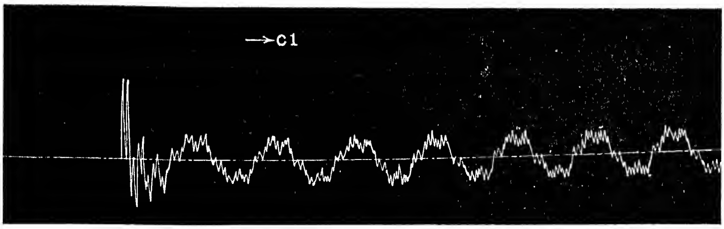
Record *B*2



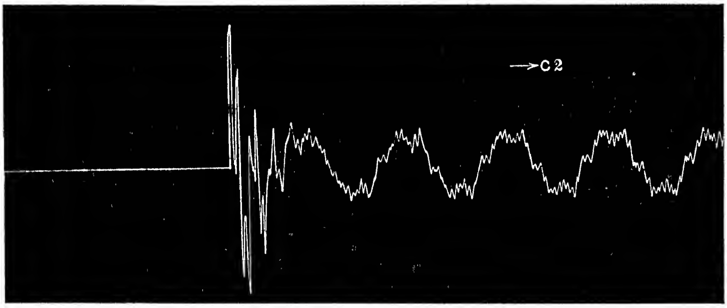
Record *B*3

line is entirely open at the generator end. Before opening the line the record shows the charging current of the transformer (vibrator I), voltage at generator end (vibrator III), and voltage at the receiver end (vibrator II). When line was opened the

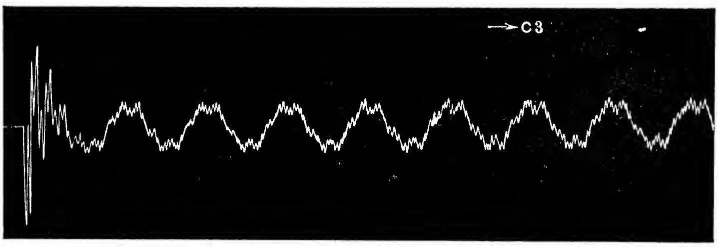
low frequency surges of voltage and current are shown. These surges are seen to be of decreasing mangitude and of longer and longer duration. The voltage wave is very flat topped, and the current wave peaked, the peak occurring at the reversal of voltage.



Record $C1$



Record $C2$



Record $C3$

In record b-3 the line was opened with only a potential transformer across the receiver end. In this case, however, the potential transformer at the generator end was connected on the line side of the disconnecting switch, and the current measured

at the generator end of the line. After the line is opened we have a closed circuit consisting of the line and potential transformers. Before opening the line the record shows the charging current of the line (vibrator I), voltage at generator end (vibrator III), voltage at the receiver end (vibrator II). When line was opened we see again the low frequency surge of voltage and current.

c. Switching Line on Line. The conditions of this test are shown by Fig. 6. Two-thirds of the line was alive and records of the current were taken as the remaining third of the line was thrown on. In this case the dead line received the initial charge from the live portion of the line, and a high frequency oscillation takes place. It is interesting to note the difference between these records (*c*-1, *c*-2 and *c*-3) and the records of the current when the whole line was thrown on a transformer (*a*-1, *a*-2 and *a*-3).

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

PROTECTION OF ELECTRICAL TRANSMISSION LINES

BY E. E. F. CREIGHTON

Introductory Summary

A review of some of the principal headings with an occasional comment will give a rapid survey of the scope of this paper. The conditions of single grounds occupy most of the treatment, although incidentally the subject of short circuits and high frequency oscillations are brought in briefly where they are particularly pertinent. The general principles of the *arcing ground suppressor* are described. Its mechanical features, consisting of an oil switch, electrostatic or electromagnetic selective relay, and safety auxiliary devices, are treated in detail. Then follows a discussion of the security with a metallic ground and the practical tests of the *arcing ground suppressor*. The electrostatic capacities of the line wires are so changed by the accidental grounds, that considerable space is given to this subject under the three heads of analogy, physical theory, and mathematical solutions. This subject has a strong bearing on the design of the *suppressor* but has only a convincing and theoretical connection with the use of it. In connection with the arcs on lines, tests are given of arc length, voltage, and currents. These are illustrated by simultaneous photographs of arcs on horns and oscillograms with curves of subsequently calculated lengths, voltages, and currents.

The second part of the paper involves a general discussion of protective problems on transmission lines. The terms " super-spark potential " and " bolt-peak " are defined. Some new theory on lightning induction on lines is given. The following

head lines show the nature of the discussions: Possibilities of using lightning arresters to protect against the "bolt-peak;" trolley line arresters; why "spill-overs" occur usually on only one insulator; numerical conceptions of the factors of induced lightning; some observations on direct strokes and their effects; where lightning will strike; what has been done to protect lines; tests of overhead grounded wires; protection by high dynamic potentials and chance; protection by corona; line construction and design from the singular standpoint of protection; conditions without the arcing ground suppressor with several photographs illustrating arcs on insulators; and finally illustrations and theory on the burning off of line wires by the electric arc.

The object of this paper is, primarily, to describe a new method of protecting line insulators against arcs to ground and the consequent vicious surges which accompany such accidental arcs, and to describe the apparatus for accomplishing this, with statements regarding its scope of application and its limitations;

Secondarily, to point out the trend of the developments in line protection, to record some experimental data relating to the problem of line protection, and, with the experience of the laboratory in mind, to speculate on certain lightning effects.

In the past considerable attention has been given to the protection of electrical apparatus. For the protection of medium- and high-tension apparatus, the aluminum arrester has had sufficiently long use to attest its undoubted value. There has, however, been no type of arrester developed suitable to the protection of line insulators and judging from our present knowledge of lightning phenomena, there is little prospect of such a development being made. In general, arresters are not suitable for line protection. Even the relief gap in the form of horns at the insulator has proved unsuitable and ineffective. There is nothing offered yet which does not involve an interruption of service when an accidental arcing to ground takes place, as well as permitting surges of high frequency and of considerable energy to play at will in the system.

In the foregoing statement that lightning arresters are never recommended specifically for the protection of insulators, the use of arresters on a trolley line is an apparent contradiction. The statement, however, is true. A further discussion is given later under the subject of protection of trolley lines.

Line Protection. The problem of line protection may, for present purposes, be divided into two parts:

First, the suppression of the arc that follows a lightning discharge over an insulator from one phase to ground. This phenomenon is the most frequent one. Apparatus is described which suppresses such an arc. It is immediately adaptable to lines on which the insulator pins are grounded—a condition which exists naturally in the use of iron towers.

Second, the prevention and suppression of short circuits between phases. This phenomenon occurs relatively rarely. Some suggestions are made later in regard to this problem, but there is not space at present to describe the work in this field. This paper has to do mostly with the first division of the problem, namely, a single grounded phase.

Circuit Changes During the Process of Grounding. In the following discussion a three-phase circuit only is considered. If the neutral were grounded through no resistance, the result

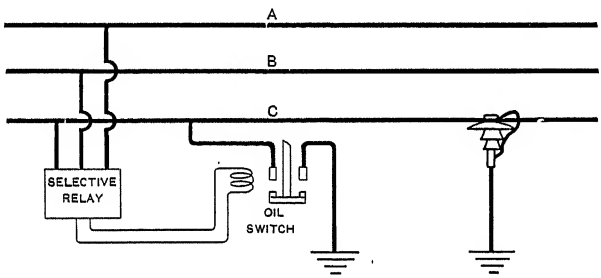


FIG. 1.—Line arcing insulator, switch, and selective relay

of an accidental ground on one phase, would be a short-circuit of the Y leg of that phase. This short-circuit would necessitate an interruption of service, therefore, we need not consider such practice at the present moment. If the neutral of the three phases is non-grounded or grounded through a relatively high resistance, then one phase may be accidentally grounded or purposely grounded without affecting the operating voltage between phases either delta or Y to any appreciable extent. The whole system becomes unbalanced electrostatically relative to the ground and auxiliary currents will be superimposed on each phase to satisfy the requisite conditions of electrostatic charges. Since the charging circuit of a line is small in comparison to the power current, except in very long transmissions, the drop of potential due to the flow of the charging current along the line is of negligible value. To begin with, the usual condition then,

is assumed; that is, that a line wire has practically the same potential above ground throughout its entire length, no matter what that potential may be. Later the exceptional cases will be considered.

General Principles of the Arcing Ground Suppressor. A three-phase transmission line under normal operation has its three phases, A, B, C, respectively at an equal effective potential above the earth. If, however, one phase is accidentally grounded as shown in Fig. 1 the potential of that phase above ground will be reduced to the effective potential drop along the arc. If this phase C has attached to it a single phase switch S which will connect it to ground, the wire will be reduced to ground potential and the arc around the insulator will be extinguished by lack of potential, *i.e.*, shunted out.

The insulator reassumes its normal condition of insulation as soon as the arc vapors are cooled below the temperature of conduction. The chilling of the arc requires, in general, but a small fraction of a second of time. If the grounding switch is now opened the circuit will assume again its normal condition of equality of potential of each phase above ground. The line is cleared of an arcing ground without interrupting the service.

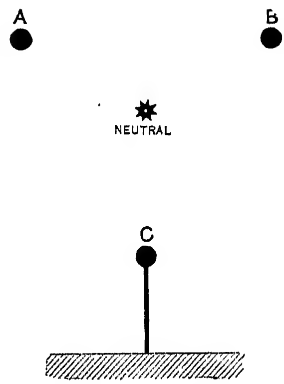


FIG. 2.—Three phases, one grounded and neutral

Before the phase C was grounded the neutral of the three phases was at zero or ground potential. After the phase was grounded, the neutral was at Y potential above ground as indicated in Fig. 2.

This is essentially true as the generator produces the same voltage between terminals. This means also that the two other phases, A and B, are now raised from Y to delta potential above ground.

Selective Relay. Between the phenomenon of the arcing ground and the closing operation of the single-pole switch there must be an intermediate device which picks out the phase that is grounded and closes the proper relay to operate the single-pole switch. Since the most evident and stable condition attending this accidental ground is the decrease in potential of the phase C toward ground and the increase in potential of the other two

phases above ground, it is natural to choose these factors to operate the selective device. In passing, it might be noted that this device cannot be operated thus independently on each phase but the three phases must operate conjointly in the selective device. In other words, if the line is not in service, and therefore all three phase at zero potential, there must be no movement of the selective device, any more than there is when all three phases are equally charged to an effective potential above ground. This selective operation is attained by connecting the three phases together mechanically. The two devices developed for this purpose are shown in Figs. 3, 4, 5 and 6.

Electrostatic Selective Relay. In Fig. 3, the circuit connections

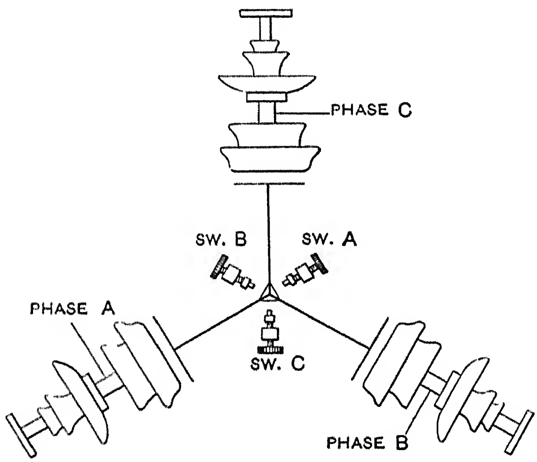


Fig. 3.—Diagram of electrostatic selective relay

are shown for the electrostatic selective relay. Three insulators are set at angles of 120 deg., facing each other in a horizontal plane. The pin of each insulator is insulated by being fastened to another insulator and connected respectively to the three phases. The electrostatic field produced at the heads of these insulators act mechanically on three aluminum plates placed in front of them and grounded as shown in the photograph Fig. 4. These three aluminum plates are connected together by three light radial rods. At the center, these three rods connect to the bottom of a pendulum, pivoted at the top so that it can swing in any angle away from the vertical. This gives a balanced mechanical system which remains stationary for all voltages so long as they are equal. If, however, as in the case

assumed, phase C is grounded, the electrostatic force on the corresponding aluminum plate is weakened and on the other two plates strengthened. The result is that the pendulum moves over against the contact, marked $S\ C$ in Fig. 3 and clearly shown in form in Fig. 4. Making this contact operates the trip coil on the single-pole oil switch, indicated in Fig. 1. This electrostatic selective relay is easily adapted to all high voltages, but the forces drop off so much for low voltages that it is there found necessary, so far, to resort to potential transformers and electromagnetic coils. The potential transformer is an item of added cost but is not a serious matter at low voltages.

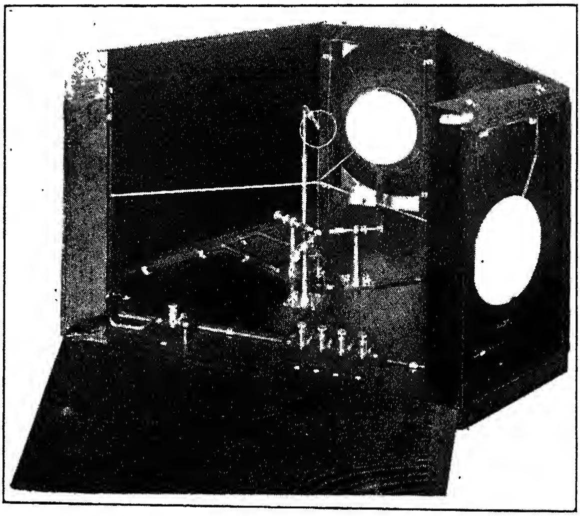


FIG. 4.—Electrostatic selective relay

The Electromagnetic Selective Relay. Fig. 5 shows a diagrammatic sketch of the connections. Three potential transformers $T\ A$, $T\ B$ and $T\ C$ are connected in Y and the neutral is grounded. The secondary of each is connected directly to a solenoid. The solenoids stand in a vertical position and each has hung over it a core of iron suspended to a three-arm lever pivoted at the center. Just above each lever is a contact point which, when closed, trips the single-pole grounding switch corresponding to the phase. The operation is the same in principle as the electrostatic relay. If the potential on the leg $T\ C$ weakens, the other two phases strengthen; there is a cor-

responding movement of the cores in the solenoids which results in the desired selective action by closing a contact.

Safety Auxiliary Devices. These devices consist of damping resistance in connection with the switch, interlocks between the three independent single phase switches, and an interlock on the selective relay, as an extra safeguard against closing two single phase switches at once. These devices will be described in order.

Damping Resistance for the Switch. Every circuit containing inductance and capacity is subject to electric oscillations when an arc takes place in any part of the circuit. Where

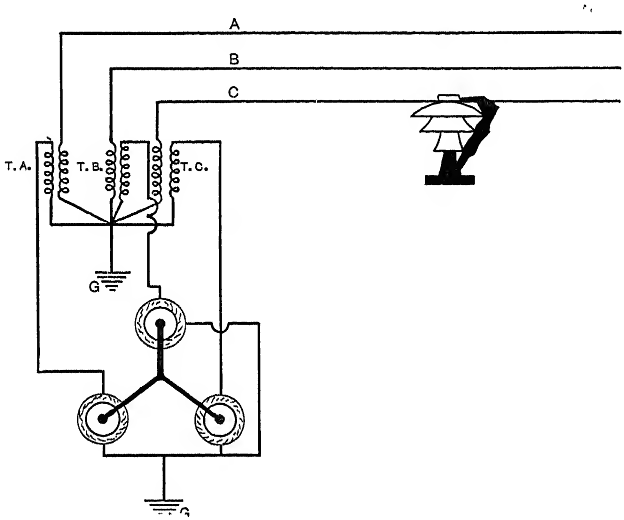


FIG. 5.—Diagram of electromagnetic selective relay

capacity predominates the arc current is seldom continuous. The current starts suddenly, and stops suddenly an indefinite number of times per cycle of the generator, according to the values of the following factors: gap length, current, potential, circuit conditions, air currents, etc. Each time the arc makes or breaks, an electric impulse is given to the circuit which sets up an oscillation. This oscillation is at the natural frequency of the circuit or multiple thereof, and its duration depends on the amount of damping, or rate of absorption of its energy. The danger from such an oscillation lies in resonance with some local circuit, such, for example, as an internal coil in a transformer, generator, potential regulator, etc. The typical behavior of

such an oscillation is shown in Fig. 6. This is the natural oscillation in a mercury arc rectifier circuit. Its natural period is 3,000 cycles per second. If an accidental arcing ground took place on this circuit which happened to have a period of 3,000 cycles, it would resonate with the transformer coils and a rise in resonant voltage would result.

Resonance implies repeated impulses or oscillations. If the arcing ground has a resistance in series equal to the critical value given by the equation $R = 2\sqrt{\frac{L}{C}}$, each single impulse will die out without oscillation. Even if the resistance is only one-fifth the critical value given by the equation above the oscillation disappears quickly. The accidental arc around an

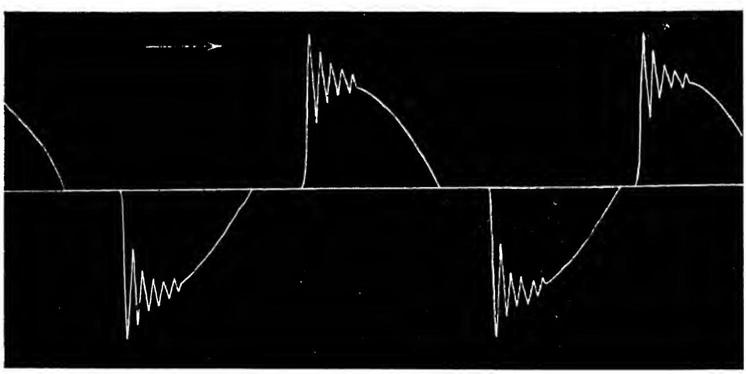


FIG. 6.—Mercury arc oscillation

insulator is extinguished as quickly as possible by the switch: it is then necessary to extinguish the arc to ground in the switch as it opens. To eliminate the dangers from oscillations, damping resistance is placed in the switch pot. This resistance is thrown in series as the switch rod moves out. Fig. 7.

Interlock Between Switches. The three single-pole switches of the suppressor are provided with a common interlocking device operated by a solenoid, which prevents any two switches from getting in the closed position simultaneously and thus causing a short circuit. In the test, all three trip coils were closed simultaneously but no switch closed. If, however, one contact preceded the others by a small fraction of a second the corresponding switch closed and locked the other two open.

Interlock on the Selective Relay. As a further precaution against accidental short circuits in the switches, the natural conditions of construction of the relays make it impossible to close two trip-coils simultaneously. The three contact points on the selective relay, which are connected to the trip-coil, are so widely spaced that the pendulum cannot swing against two at the same time.

In the case of a double ground the selective relay can be either made inoperative or made selective of one of the grounds. The selective relay, as shown in the preceding illustrations, is inoperative on short circuit of either delta or Y. The pendulum swings between contacts of the trip-coils.

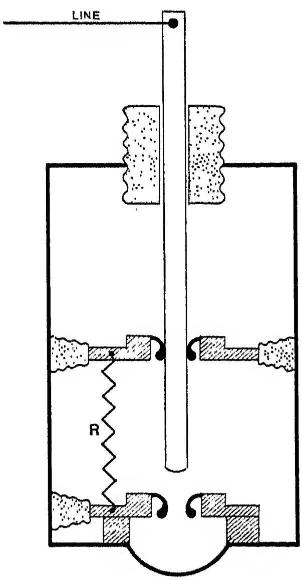


FIG. 7.—Damping resistance in the switch pot

Second Stroke Lock Device for Punctured Insulators. So far, an arc around an insulator has been considered. In this circumstance the protecting switch closes, and opens automatically a fraction of a second later. If, on the other hand, the insulator is defective and punctures, the line potential will reëstablish an arc to the iron pin. This will cause the switch to close again. This second time it is locked shut until the attendant opens it by hand. This second stroke lock comes into action only if the switch starts to close the second time immediately after the first time. In other words, if the switch stays open for a fraction of a second after the first stroke, the second stroke lock becomes inoperative. With the arc shunted out, the dangers from arcing ground surges are avoided. The system can continue to operate with a metallic ground until the fault is located and the faulty line cut out. The chief source of danger in such operation is in the possibility of a second stroke of lightning establishing another arcing ground on another phase before action is taken to clear the feeder.

Arcing Ground Suppressor for Cable Systems. When the insulation of a cable fails, the damage is permanent. The distance from the conductor to the metallic sheath is so small that

the normal impressed difference of potential is sufficient to re-establish an arc, even if it were automatically extinguished. It is seldom indeed that an accidental arc is established in a cable from conductor to conductor. Two weak spots seldom fall together. The usual case is a failure of one conductor to the sheath. When this occurs there is nothing to be done but ground the faulty phase to the sheath and thus extinguish the arc. This will prevent the arc to ground burning the insulation into an adjacent phase, melting up everything in the neighborhood with a power arc, and, by the explosive action of the arc, blowing up the surrounding conduit or manhole.

The foregoing requirement simplifies the switch operation. In the protection of an insulator, the switch closed and opened again automatically. For the protection of cables it is necessary for the switch to close once and stay closed until the feeder has been cleared.

Security with a Metallic Ground. With one phase grounded the factor of safety on the other two phases in their insulation to ground is somewhat reduced by the fact that the potential is increased 73 per cent—the increase from Y to delta potential. Since every cable should have an insulation which will carry double delta potential, the increase to only delta potential should not produce a serious strain. There is no arc to produce high frequency, therefore, there is left to consider the possibility of obtaining resonance in any part of the circuit at the frequency of the generator and of such harmonics as may be prominent. The capacity current flowing into the two non-grounded phases must pass through the inductance of the generator and connecting transformers. Taking into account the possible wide variations of inductance and capacity in all systems, one is forced to acknowledge a chance of obtaining resonance with a phase metallically grounded, but resonance in itself has no terrors. The increment of energy in the resonant surge is always small relative to the energy given out even by a small transformer. If a transformer, for example, is loaded even with a few lamps, the resonant potential will be held down by the absorption of the energy of the surge in the lamps. If, on the other hand, the transformer is not loaded and it is in a condition of resonance, its resonant energy will be absorbed by some parallel loaded transformer. When the possibility of resonance internally between coils of a transformer is considered it can be stated positively I believe that there is none.

The natural frequency of a local surge between coils is invariably too high to resonate with the frequency of the impressed potential from the generator. As an example, a 350-kw. 11,000-volt transformer has a natural frequency internally around 90,000 cycles per second. An arc-light transformer has a natural frequency around 3,000 cycles per second. These two examples show such high values of frequency that there is no apparent danger of bringing it within the range of generator frequency.

There are special and unusual conditions which need not be considered in detail here. Such, for example, as unloaded open-delta transformers coöperating with an accidentally

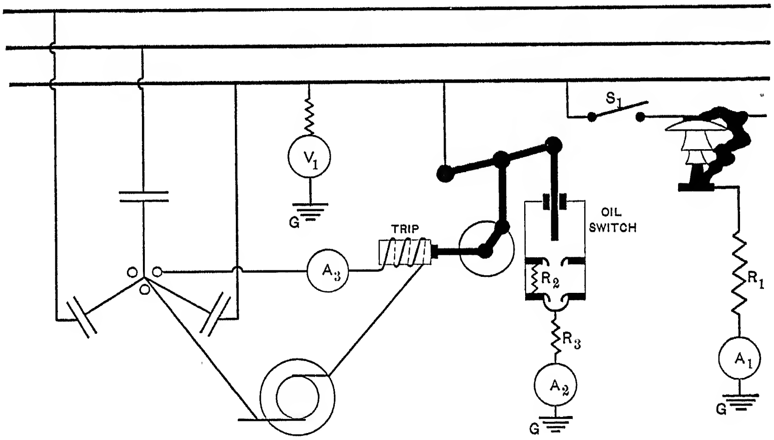


FIG. 8

broken line wire. The operation with open delta is decidedly bad practice, from a protective standpoint, and should be used in general only in emergencies. At any rate, the prevention is always to keep some load on the transformers or circuits.

As a further and final safeguard against possible rises in resonant voltages when a phase is metallically grounded, a reasonable amount of resistance can be kept in the circuit to ground. This resistance will absorb the resonant energy if it appears. There is a limitation set on the amount of resistance by the permissible IR drop. The IR drop must not be such as to reëstablish the arc at the fault.

Practical Tests of the Arcing Ground Suppressor. The general scheme of connections for the analytical testing of the arc sup-

pressor is shown in Fig. 8. The tests were made on a line of the Schenectady Power Company, 21 miles long. The delta potential is 33,000 to 35,000 volts at 40 cycles.

Commencing at the right in Fig. 8 the switch S_1 completed the circuit through the defective insulator, the series resistance R_1 and the oscillograph vibrator A_1 to ground. The insulator was made defective by means of two small wires from cap and pin respectively which were held within sparking distance of each other. The arc would form and burn the fine five-mil wire into a full length arc. With considerable resistance in series with the arc the latter was quite unstable. Since there was no apparatus on the line there was nothing but the inductance of the step-up transformer to aid in making a stable arc. The small value of capacity and the corresponding small value of grounding current prevented the formation of any long and vicious arc. However, the gap length around the insulator was shortened until the arc would, when started, hold continuously. The resistance R_1 was varied from a high value to a low value in order to test and adjust the sensibility of the selective relay. The ammeter A_1 gives the upper record in the oscillograms that measure the grounding current of the arc.

Next to the left in Fig. 8 is represented the single-pole oil switch connected to the same phase and ground. The internal resistance in the oil pot is shown as R_2 and the auxiliary resistance as R_3. The ammeter A_2 next to the ground gives the middle record in the oscillograms which measure the grounding current of the switch.

Next to the left is represented the oscillograph voltmeter V_1 between the same phase and ground.

On the left the selective relay is represented diagramatically with its intermediate connections to the trip-coil of the oil switch. An ammeter A_3 gives a record in a later oscillogram of the current in the trip-coil circuit.

Referring to Fig. 9, oscillogram 8, time is reckoned in cycles, with the number placed just above the points of interest on the records. The instant that the arcing ground commenced (see upper record) is taken as zero time. The current started at the peak of a wave. There is no rush of current into the capacity of the line because a high series resistance was placed in circuit with the arcing insulator. This resistance was used primarily to prevent a large drop of potential between this phase and ground, in order to test the sensibility of the selective relay. This is

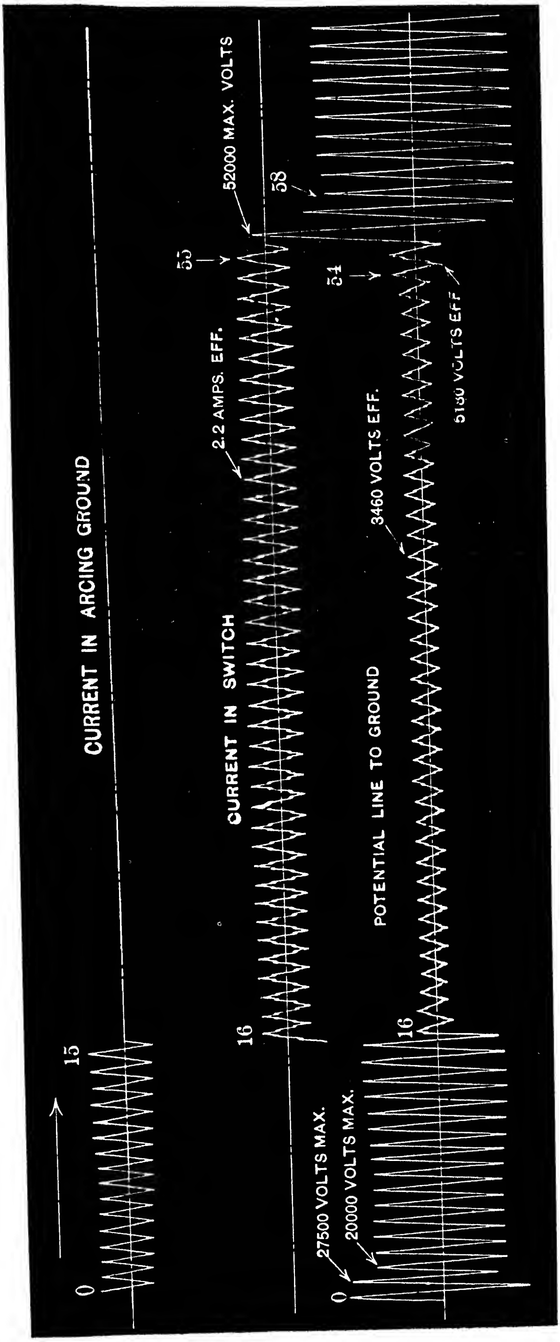


FIG. 9.—Oscillogram 8 on test of arcing ground suppressor

demonstrated on the lower record. The voltage from line to ground drops from normal 27,500 volts maximum at zero time to 20,000 volts at the end of a half cycle. This is 27 per cent drop only or 73 per cent of full potential. It represents the condition of an arcing insulator situated hundreds of miles from the generating station.

Following along the upper record, the arcing ground is extinguished in $15\frac{1}{2}$ cycles. The arcing ground is not reëstablished.

In the middle record, the current in the switch, which shunted out the arc to ground, commences with a rush at $15\frac{1}{2}$ cycles. This current rush is due to the fact that there was less resistance in series with the grounding switch than there was in circuit with the arcing insulator.

During these $15\frac{1}{2}$ cycles of arcing ground, the selective relay moved over to its proper contact, the current was applied to the trip coil of the switch, the plunger moved up and tripped the latch, and the switch rod moved down to its first contact. The proportional time absorbed by each of these phenomena is not measured here, although a partial separation is made in a later oscillogram.

Referring to the lower record, it may be noted that the switch rod strikes the contact connected with the internal resistance two cycles ($15\frac{1}{2}$ to $17\frac{1}{2}$) before it reaches its home contact. When the switch rod reaches its home contact the potential from line to ground does not drop to zero in this case because an extra resistance of about 1000 ohms was left in series with the switch.

Referring to the middle record, the oil switch remains closed from $15\frac{1}{2}$ to $55\frac{3}{4}$ cycles, practically one second. When the current ceases in the oil switch it happens that it leaves the potential of the corresponding phase at a value different from what it should have in a balanced non-grounded condition. The oscillogram indicates in the lower record that the potential should have been a negative peak value but was actually about zero; consequently when the generator changed from a negative peak to a positive peak it carried the potential to nearly double value (52,000 volts maximum in the 56th cycle). In the following cycle the electrostatic unbalancing of the system partially adjusts itself, and in the next following cycle, the 58th, the three phases are symmetrical with the zero or ground potential. This adjustment to a balanced condition seems to take place through the resistance of the voltmeter.

Reviewing the information given by this oscillogram, the arcing ground was extinguished by the protecting switch in $15\frac{1}{2}$ cycles, thus suppressing the resulting surges. The oil switch then took a second to open and clear the circuit. During this test and all others on this line a needle gap was maintained between phases (33,000 volts) but at no operation of the switch did the gap, set at 45,000 volts, spark. When the line was switched on or off, however, the gap would invariably spark. The freedom from surges was obtained by using series resistance, already referred to.

In Fig. 10, oscillogram 9, the principal feature of the record lies in the fact that the relay was made more responsive and cut down the time of arcing ground to eleven cycles. During these eleven cycles the lengthening of the arc around the insulator

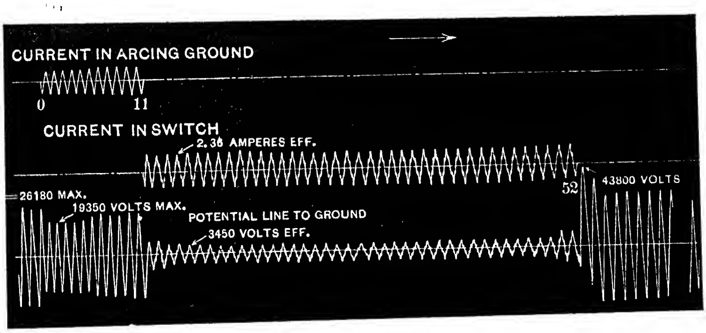


FIG. 10.—Oscillogram 9 on test of arcing ground suppressor

can be traced by the increase in voltage from line to ground through the arc as shown in the lower record. The potential drops to 19,350 volts at the beginning of the arc and rises gradually to nearly full Y voltage again. Since the potential from line to ground is only slightly disturbed, it is evident that no vicious surges of the system as a whole could result.

In a subsequent test the voltage drop from line to ground was only 11 per cent. The relay was adjusted not to respond. It seems undesirable to have the selective relay too sensitive for fear it might respond to some single-phase Y overload. It can be made non-responsive to the particular unbalancing of phases due to a single-phase delta overload.

Fig. 11, oscillogram 26, shows on its upper record the current in the selective relay and trip-coil circuit. The selective relay

required about four cycles to close after the arc started (shown by the drop of potential on the lower record). Initially there was one little rebound of the relay contact (shown in the upper record) and then a gradual, although variable, building up of the direct current. The variations are due, in part, to the line drop when the motors attached to the switches started up.

Fig. 12, oscillogram 33, was taken at a higher speed to show the harmonics in the ground current. There was a poor contact which caused some sparking. These sparks set up extra oscillations superimposed on the harmonics.

Fig. 13, oscillogram 35, was taken with the expectation of showing the second lock shut operation of the switch, but the film was not quite long enough to record the second closing. Instead of using an arc around an insulator, metal electrodes set a

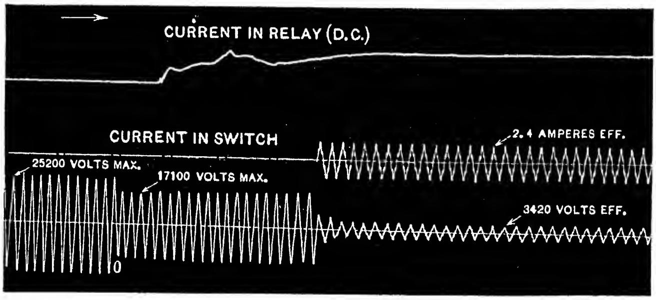


FIG. 11.—Oscillogram 26 on test of arcing ground suppressor

little below spark potential to ground were used, so that the arc would restrike after the first extinction by the suppressor. Some other circuit conditions were also changed; the deflection of the current in the arcing ground was increased and the resistance in series with the arc reduced to a small value. The effect of this is shown by the low potential from line to ground (3800 volts) on the lower record during the arc. Also the external resistance in series with the grounding switch was reduced to zero. When the switch rod reaches its home socket, the potential to ground is reduced to zero. The internal resistance in the switch pot delays this reduction for two cycles after the arc is extinguished and again raises the potential through the pot resistance two cycles before the switch opens and restrikes the arc. The records are so similar to the previous ones that no further comments are necessary except perhaps to draw attention to a surge of ground

current of 13.7 amperes (3.6 times normal) in the arcing circuit (upper record) at the moment of restriking the arc. The deflection passed through both the other records and nearly reached the bottom edge of the film. This current rush was due to the electrostatic charging current of the line when connected at nearly

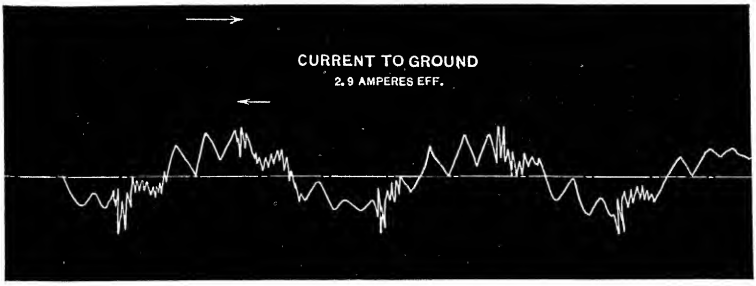


FIG. 12.—Oscillogram 33 on test of arcing ground suppressor

the peak value of dynamic potential with only a low resistance in series. This is the effect which usually starts the disastrous phenomena of arcing grounds. The voltage from line to ground at this instant (lower record) shows a rise of potential for an instant to nearly normal value, when the grounding arc struck again.

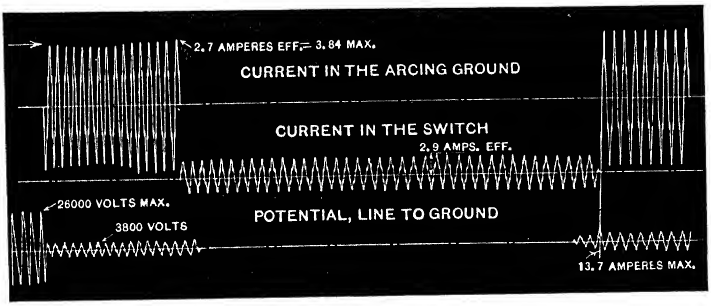


FIG. 13.—Oscillogram 35 on test of arcing ground suppressor

Territorial Limitation of the Operation of a Single Arc Suppressor. The best location of the arc suppressor is usually at the power house, although cases may arise where some central switching station gives greater convenience. To get figures on the limitation of a device, the line constants of a 45-kilovolt system are used as a basis. The Y potential to ground is nor-

mally 26 kilovolts the charging current about 0.15 amperes, per mile and the inductive reactance about 0.75 ohms per mile and impedance 0.86 ohms per mile at 60 cycles.

Assume one-phase grounded at the power house by the operation of its protecting switch caused by an insulator arcing over far out on a straight away line. The potential of this phase at the generator is zero, but the line wire is not zero throughout its entire length. There may be a considerable potential at the faulty insulator. This is found by multiplying the total charging current in the line by half the impedance.

Since all the treatises on the subject of line capacity assume a normal condition of no grounded phase, the electrostatic capacity to the ground can be and is neglected. When a phase is grounded the several factors take on variable degrees of importance and become confused. On this account a discussion is here given of grounded phase capacities; first, in an analogy,

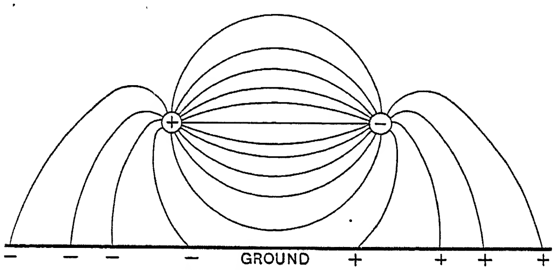


FIG. 14.—Electrostatic flux, non-grounded condition

second, in its physical theory, and third, in its mathematical theory.

Analogy of Grounded Phase. Grounding a phase of an electrical system has about the same electrical effect as the mechanical shifting of a cart wheel axis from the center of the wheels to some excentric point out near the rim of the wheels. The body of the cart would rise and fall by the amount of the excentricity. Theoretically, it would not require any more total energy to pull the cart because the energy given to lift the body is returned when it descends. At a high speed the cart would progress by jumps. In a three-phase electric circuit with one phase grounded all the apparatus will rise and fall in potential during every half-cycle. If there is resonance, the rise will be more than Y potential. If the ground is arcing, the electrical conditions correspond to a flat wheel on the cart. Every time it drops it bumps and sets up vibrations or oscillations throughout the body or system.

Physical Theory of a Grounded Phase. For simplification assume the condition of a single-phase circuit with the wires equally distant from ground. If the two wires are connected to a generator, one wire, at an instant, will be charged to a definite positive potential above earth potential and the other to an equal negative potential below earth potential. There will be two sets of static fluxes or displacement currents. One set passes between conductors without intervention. The other set passes between conductors with the intervention of the earth's surface. In terms of displacement, the earth being a conductor, collapses all the static lines that would have existed in that same volume. In so doing it shortens the path between conductors slightly and by releasing the static stress in that neighborhood, lines of static force from elsewhere in the static field will be pressed into the earth in order to balance all the forces. The

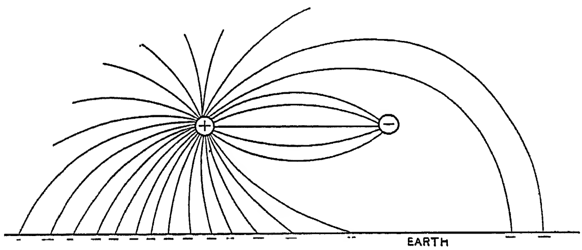


FIG. 15.—Electrostatic flux, one grounded wire

conditions are shown in Fig. 14. According to the older method of representation there is both a negative and positive charge at zero potential induced on the earth.

Anything which shortens the electrostatic lines of force between two conductors increases the displacement in the dielectric. The total displacement in the dielectric is the quantity of electricity in the electrostatic charge. Since the definition of the capacity is the ratio of the quantity of static electricity to the electric pressure, the capacity is increased by anything which shortens the static lines of force. When the earth is at a relatively great distance from the two line conductors it will not be in a dense part of the electrostatic field between conductors and will not, therefore, shorten appreciably any great percentage of the displacement flux. In other words, the presence of the earth will not much affect the electrostatic capacity of the wires.

If now the negative wire is connected to earth, all the electro-

static lines of force between that conductors and earth will be collapsed by the fact that the displacement in the dielectric is relieved by a conduction current through the vertical *grounding conductor*. Following along any line of force in Fig. 14 from positive wire to negative wire through the earth, any static line of force has been shortened by one-half. The conditions of dielectric displacement are represented in Fig. 15. There are several things that have taken place:

First, the electrostatic flux between the negative wire and the ground has disappeared.

Second, the electrostatic flux between the positive wire and the ground has expanded to fill up the space left free by the collapse of the flux between the negative wire and ground.

Third, the entire field of flux has been bent down toward the earth. The earth is now one terminal and by its great surface gives a relatively shorter distance for many lines which previous to the grounding took long curved paths between wires.

Fourth, due to the two causes, namely, disappearance of negative flux to ground and stealing of line to line flux, the flux or dielectric displacement from the positive wire to earth has been greatly increased.

Fifth, in the first enumeration above there is inferred that a current flows along the *grounding conductor* to the negative line when the corresponding electrostatic flux collapsed. There is an additional current in the *grounding conductor* due to the increase in flux from the non-grounded wire to earth. It should be remembered that the generator is the source of energy and is connected to the line wires. Therefore, the only way the single charge on the surface of the earth can get there is through the *grounding conductor*. The grounding conductor is not shown in Fig. 15 as it is not assumed to be in the plane of the paper.

Sixth, in the foregoing fifth enumeration it has been stated that the grounding offers a shorter path for some of the lines of force between wires by way of the earth. In other words, for the same potential difference between wires there is less displacement current to the grounded line wire—its electrostatic capacity is less. There is another significance to this statement. Some of the charging current to satisfy the capacity between wires which formerly flowed along the negative wire now flows to the earth through the grounding connection.

Seventh, the positive or non-grounded wire has a greater flux or displacement current for the same difference of potential

between generator terminals and, therefore, its capacity is increased. In other words, it has a greater charging current after grounding the other line wire than before.

The conditions are shown diagrammatically in Fig. 16. The charging current to ground is A_2, to the negative wire is A_1 which is much below normal value, and the total capacity current to the non-grounded line wire is A_1+A_2.

Summing up this physical theory, the grounding of a wire of a single-phase system does the following things in general:

1. It brings into prominence the capacity of the non-grounded wire relative to the earth. This capacity corresponds to the condition of a single overhead conductor with earth return.

2. Since this capacity is distributed and the grounding connection only at one point, the capacity current must flow along

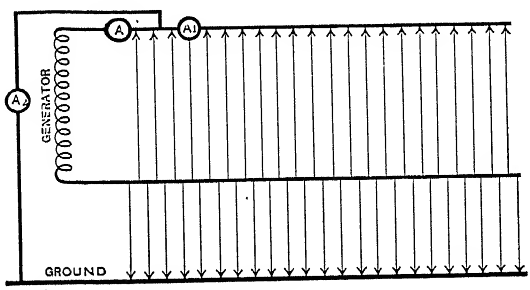


FIG. 16.—Electrostatic flux, one grounded wire (longitudinal view)

the wire to the earth connection during each half cycle of the generator.

3. The grounded wire must have a small current supplied to it to keep it at zero potential.

The relative values of the foregoing factors must be determined by calculation.

With the solution of the value of current to ground in hand, the proof is easy of the initial statement that a grounded wire does not remain at zero or ground potential throughout its length. It may be added that its potential difference to ground varies directly as the distance away from the grounded point of the line. The charging current that flows into and out of the grounded phase wire in an endeavor to keep it at zero potential must pass through the inductance and resistance of the wire. Using the well known

method of assuming the capacity of the total length of line concentrated at half the length, and using the charging current of this condenser passing through half the inductance of the line, the drop of potential from the protecting grounding switch to the faulty insulator assumes the following form:

$$e = \tfrac{1}{2} L\, w\, I_c$$

per mile, where L and I_c are the inductance and charging current per mile. Since the inductance and capacity current both have to be multiplied by the number of miles to the faulty insulator the equation for the potential becomes

$$e = \tfrac{1}{2} L\, w\, I_c \times (\text{miles})^2$$

For a 45-kilovolt line the constants assume the approximate value of 0.06. For a 100-mile (161-km.) line the drop should be about 600 volts with a charging current of about 15 amperes. At 200 miles (322 km.) the potential drop should be about 2400 volts.

Such a straight away length of line would be unusual but radial trunk lines each with branches with emergency loops may give a considerable length of line. In the case of multiple branches, each branch may first be considered independently, and then combined with its corresponding length of trunk line inductance. In the case of radial feeders, the grounding current is the sum of all the capacity currents but the drop of potential between the arcing ground and the station involves only its own capacity current after the suppressor grounds the phase at the station.

The foregoing voltages may be considered the usual values. The actual potential drops may be different due to three causes:

1. The apparatus has capacity.
2. An overhead grounded wire introduces a favorable element.
3. The instantaneous values of charging current during an arcing ground are many times as great as the 60-cycle charging current. Numerous oscillograms illustrating this condition were shown at the Frontenac meeting of the Institute by Mr. S. D. Sprong and the writer. The sudden current rushes when the arc is relighted at considerable potential produce a correspondingly higher drop of potential at the faulty insulator. There are still other factors which enter. Sufficient to say, however, that tests on the Southern Power Company's System, one of

the largest in the world, show that the length of line that can be protected by a single protector is ample to cover all existing systems.

Mathematical Solution of Capacities.—In the following mathematical solutions the fundamental equation for the potential of a conductor in electrostatic units is used as a starting point.

$$V_1 = 2\ Q_1 \log_\epsilon \frac{\text{distance between wires}}{\text{radius of wire}} \tag{1}$$

where V_1 is the potential to earth or neutral and Q_1 the quantity of electricity per unit length.

$$V = 4\ Q \log_\epsilon \frac{\text{distance between wires}}{\text{radius of wire}} \tag{2}$$

where V is the total potential. The former is necessarily the equation for a wire with ground return because all the potential is between the wire and neutral and the latter for two wires with a neutral between them.

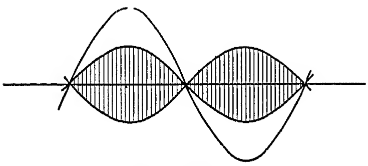


FIG. 17

Much confusion in writing potential equations will be avoided if it is initially noted that our usual linear representation of a sine wave of potential, rising above and successively falling below zero is an inaccurate and misleading representation of what is taking place in an alternating current circuit, although, it must be confessed, it is for general use a convenient form in which to use it. The oscillograms of voltage or potential (so called) repeat this inaccuracy and further fix the misconception. The bifilar oscillograph never gives a potential curve. It produces a current curve that is proportional to the difference of potential. This potential difference produces a current first in one direction then in the other, which gives the misrepresentation of the potential of the generator. For example, an oscillogram giving a positive peak potential of 140 volts indicates that when the potential reverses to the same negative value that the total change of potential is 280 volts. The actual maximum difference of potential either instantly or successively is only 140 volts. In Fig. 17 is shown the oscillogram in the large sine wave and the real potential waves in the twin curves which increase one positively

and the other negatively simultaneously; each curve has a value of $\frac{1}{2}\, E \sin \alpha$. To bring equations (**1**) and (**2**) to practical units involves the value of the velocity of light. Slightly varying values have been used. In volts, coulombs, microfarads, and common logarithms the equation for potential of a mile length of two parallel overhead wires becomes:

$$V = \left(\frac{4}{.078} \log \frac{r_{12}}{r}\right) Q = \left(51.3 \log \frac{r_{12}}{r}\right) Q \qquad \textbf{(3)}$$

r_{12} is the distance from the center of one wire to the surface of the other, or with sufficient approximation from center to center of the aerial wires, Q is the number of coulombs per mile. The value 0.078 is the transformation constant depending on the velocity of light, logarithms, etc., mentioned above. From the authors the writer has immediately at hand, the following values are found: 0.0772, 0.0775, 0.0776, 0.0784 and 0.0845.

The constant 0.078 corresponds to a velocity of light of about 184,000 miles (29.6×10^9 cm.) per sec. The constant 0.0845 corresponds to a velocity of 179,000 mi. (28.8×10^9 cm.) per sec.

The assumption is made that the law of potential of a conductor due to its own charge and that of several charges around it is known. Then for the two conductors in Fig. 17*a* with the dimensions shown, positive charges on both conductors and the earth as a return.

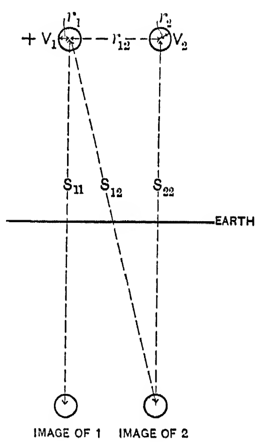


FIG. 17A

$$V_1 = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 + \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 \qquad \textbf{(4)}$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 + \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \qquad \textbf{(5)}$$

The factors in parenthesis are known as potential coefficients.

Starting with equations (**4**) and (**5**) a number of numerical problems will be solved all of which unless otherwise designated

will have the following constants. Size of all wires the same, *viz.*, No. 0 B. & S., radius of wire, $r_1 = r_2 = 0.1624$ in. (4.07 mm.). Distance between centers, 48 in. (1.219 m.). Height above ground 360 in. (9.14 m.); therefore, $s_{11} = s_{22} = 720$ in. (18.28 m.). The diagonal distance S_{12} is about 722 in. (18.33 m.).

Problem 1. Find the capacity of wire 1 when wire 2 is used as return. For convenience an instant in time will be chosen when wire 1 is positive in every case following. Wire 1 is at $+V_1$ above zero potential and wire 2 is at $-V_2$ potential below the earth. The total potential difference is $V_1 + V_2 = V$. The generated potential is equally positive and negative and since the two wires are of the same size and parallel with the earth, they are in symmetrical relation and therefore $V_1 = -V_2$. The same argument holds in respect to the quantities of electricity, therefore $Q_1 = -Q_2$. Equation (4) then becomes

$$V = \left[51.3 \left(\log \frac{s_{11}}{r_1} - \log \frac{s_{12}}{r_{12}} \right) \right] Q_1 \tag{6}$$

By combining the logarithms the total capacity of wire 1 may be written

$$C_1 = \frac{1}{51.3 \log \left(\frac{s_{11}}{s_{12}} \frac{r_{12}}{r_1} \right)} = \frac{1}{51.3 \left(\log \frac{s_{11}}{s_{12}} + \log \frac{r_{12}}{r_1} \right)} \tag{7}$$

This equation for the capacity between conductors has an unfamiliar appearance due to the presence of $\log \frac{s_{11}}{s_{12}}$ which represents the effect of the ground in increasing the capacity of the conductors. The ratio of the height of a conductor above its image to the diagonal distance to the image of the other conductor is approximately one for all usual conditions of overhead wires. In this case the log of the ratio $\frac{720}{722}$ produces only 0.000003 microfarads difference in the capacity of a wire. The capacity of wire 1 cones to 0.0079 microfarads, or more conveniently expressed 7.9 milli-microfarads.

In order to learn when the presence of the ground might become a factor in the capacity worthy of consideration the two wires were separated to 150 in. (3.81 m.) and the height above

the earth calculated such that an error of one per cent would be involved in the value of capacity when the presence of the earth is neglected. The height of the wires is 16 ft. (4.87 m.) It is evident that it would be necessary to string the wires on separate pole lines to make it worth while to use the complete equation.

The standard simplified equation of an overhead wire and return with no grounds on either is

$$C = \frac{1}{51.3 \log \frac{r_{12}}{r_1}} \text{ microfarads per mile.} \tag{8}$$

Problem 2. What is the capacity of wire 1 when wire 2 is grounded? And under this condition what is the capacity of wire 2 and the earth? What is the distribution of charge between wire 2 and the earth? In equation (**4**) and (**5**) the following new conditions are introduced. The potential of wire 2 becomes zero, $-V_2 = 0$. The potential difference between the wires remaining constant, wire 1 rises to $V_1 + V_2 =$ say V. The charge Q_2 remains negative at zero potential.

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 - \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 \tag{9}$$

$$O = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 - \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \tag{10}$$

With wire 1 connected to one terminal of the generator, and wire 2 and the earth to the other terminal, there are evidently three quantities of electricity to be considered, namely $+Q_1$ on wire 1 and an equal negative charge distributed between wire 2 (*i.e.*, Q_2) and the earth. The quantity of electricity on the earth is not represented in the equation directly, therefore, it must be found from $Q_1 - Q_2$. Equation (**10**) gives immediately the ratio of charge between wires 1 and 2 and, therefore, also the ratio of capacities C_1 to C_2.

$$Q_2 = \frac{\log \frac{s_{12}}{r_{12}}}{\log \frac{s_{22}}{r_2}} Q_1 \tag{11}$$

Substituting equation (**11**) in equation (**9**) gives an expression from which the total capacity of wire 1 can be taken.

$$C_1 = \frac{1}{25.65 \log \dfrac{s_{11}}{r_1} - \dfrac{\left(25.65 \log \dfrac{s_{12}}{r_{12}}\right)^2}{25.65 \log \dfrac{s_{22}}{r_2}}} \qquad (\mathbf{12})$$

In the numerical example this gives 11.9 milli-microfarads per mile for wire 1. By grounding wire 2 the capacity of wire 1 has increased from 7.9 to 11.9 milli-microfarads which is 153 per cent.

The ratio of the quantity of electricity Q_2 on wire 2 to the quantity on wire 1 is

$$Q_2 = \frac{1.176}{3.647} Q_1 = .322\, Q_1 \qquad (\mathbf{13})$$

Since wire 1 contains the total quantity of electricity and wire 2 has 32 per cent of the opposite sign, the rest, namely 78 per cent, is on the earth.

The capacity of wire 2 has been reduced by being grounded. From equation (**13**) it can be found directly, or by substituting equation (**13**) in equation (**9**) again it can be expressed as follows:

$$C_2 = \frac{1}{\dfrac{\left(25.65 \log \dfrac{s_{11}}{r_1}\right)^2}{25.65 \log \dfrac{s_{12}}{r_{12}}} - 25.65 \log \dfrac{s_{12}}{r_{12}}} \qquad (\mathbf{14})$$

Numerically this becomes in the example 3.83 milli-microfarads.

The capacity of wire 2 drops, on grounding, from 7.9 to 3.83 which is to 48½ per cent. In other terms, wire 2 lost 52 per cent, which is just about the amount gained in capacity by wire 1 due to the grounding of wire 2.

Problem 3. One wire with earth return, the other wire being insulated. In this case the potential of wire 1 must be taken, as in the 2nd example, as twice the potential to neutral, that is $2\, V_1 = V$. The symbol for the potential of the insulated wire 2 remains V_2 as it now is. Since, however, it is insulated its

charge Q_2 is zero. There will be a separation of equal charges of positive and negative electricity due to the electrostatic induction from wire 1 and the earth, or in other terms, some of the electrostatic flux from wire 1 will pass into and immediately out of the wire 2 in a general perpendicular direction. Since the path of the electrostatic flux is shortened by only the diameter of wire 2, the presence of wire 2, which is at some distance from wire 1, will have no appreciable effect on its value of electrostatic capacity. Equations (**4**) and (**5**) become:

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 \tag{15}$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 \tag{16}$$

The capacity of wire 1 is

$$C_1 = \frac{1}{25.65 \log \frac{s_{11}}{r_1}} \tag{17}$$

In the numerical example it becomes 10.64 milli-microfarads. This capacity of a single wire with ground return is 135 per cent of that of a wire when two wires with no grounding exists, and 89½ per cent of its value when wire 2 is grounded.

Since wire 2 has no charge its capacity is useless. Its potential may be found by substituting the value of Q_1 of equation (**15**) in equation (**16**).

$$V_2 = \frac{\log \frac{s_{12}}{r_{12}}}{\log \frac{s_{11}}{r_1}} V \tag{18}$$

Numerically, this gives $V_1 = 0.322\ V$, the fraction 0.322 is the value of the mutual capacity of wires 1 and 2 previously determined.

Problem 3*a*. Distance between two non-grounded wires to give the same capacity as one wire with earth return. It has been demonstrated that one No. 0 B. & S. wire with earth

return at 30 ft. (9.14 m.) distance gives a greater capacity than a return wire at 48 in. (1.21 m.). The ratio is 10.64 to 7.9. How close will these two non-grounded wires have to be placed to give 10.64 milli-microfarads? The answer is 10.82 inches (25.72 cm.)

Problem 4. When two overhead wires are connected to potentials of the same sign and a ground return is used, the conditions are similar to those that Heaviside solved for telegraph circuits some thirty years ago.

Assume the conductors are of the same diameter and connected to the same bus bar. This corresponds in practice to the condition of two wires of the same phase but of a different circuit on the same pole line.

Then $+V_2 = +V_1$, and Q_2, no matter what its value, is equal to Q_1 so long as the two wires are at the same height above ground and have similar environments, Q_1 and Q_2 are both positive.

The equations of the potentials take the following forms:

$$V_1 = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 + \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_1 \qquad (19)$$

$$V_2 = \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 + \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 \qquad (20)$$

The capacity of either wire 1 or wire 2 is:

$$C_1 = C_2 = \frac{1}{25.65\left(\log \frac{s_{11}}{r_1} + \log \frac{s_{12}}{r_{12}}\right)} = \frac{1}{25.65 \log \frac{s_{11}\, s_{12}}{r_1\, r_{12}}} \qquad (21)$$

The corresponding numerical solution for the factors chosen previously, gives the value of 8.1 milli-microfarads for each wire to ground. Since the two wires are at the same potential their mutual capacity is useless.

When wire 1 alone was used it gave 10.64 milli-microfarads to ground but when 1 and 2 are used together wire 1 gives only 8.1 milli-microfarads (76 per cent) to ground. Wire 2 has the same capacity to ground, and since the two wires now form parallel condensers the total capacity to ground is 16.2 milli-microfarads. It should be noted that the two wires in parallel

give a greater capacity than one wire but not twice as great. The ratio for two No. 0 wires spaced 48 in. (1.21 m.), 30 ft. (9.14 m.) above ground, is 153½ per cent increase in capacity over one wire. In other words, one of these wires is in the electrostatic field of the other and can not therefore add its full displacement flux.

If the two wires were on separate pole lines then one would be well out of the region of dense flux of the other and the capacities of the two together toward earth would, therefore, be more nearly equal to twice the capacity of one toward earth. As an example, take a spacing of 100 ft. or 1200 in. (30.48 m.) between lines instead of 48 in. (1.21 m.). This gives a capacity for each wire toward ground as 10.52 milli-microfarads.

The two wires as parallel condensers give twice 10.52 milli-microfarads equal 21.04 milli-microfarads which is about 1.98 (nearly twice) the capacity of one alone toward ground.

Problem 5. The capacity of wire 1 to wire 2 is indeterminate in this foregoing case. It becomes determinate if wire 1 and wire 2 are not connected together and are charged to a different positive potential. This condition corresponds to a telegraphic circuit, a problem that Mr. Oliver Heaviside included in his general solution. This solution is reproduced here in terms of practical units, to bring out the relations of "capacity coefficients" and "mutual capacity coefficients."

It will prevent confusion if it is emphasized now that the "capacity coefficient" is not the capacity except where the "mutual capacity coefficient" is associated with a charge at zero potential.

Equations (**4**) and (**5**) can be simplified for purposes of convenience by the use of "potential coefficients" as follows:

$$V_1 = p_{11}\,Q_1 + p_{12}\,Q_2 \tag{22}$$

$$V_2 = p_{12}\,Q_1 + p_{22}\,Q_2 \tag{23}$$

The solution of these equations in terms of quantity give

$$Q_1 = \frac{p_{22}}{p_{11}\,p_{22} - p_{12}^2}\,V_1 - \frac{p_{12}}{p_{11}\,p_{22} - p_{12}^2}\,V_2 \tag{24}$$

$$Q_2 = -\frac{p_{12}}{p_{11}\,p_{22} - p_{12}^2}\,V_1 + \frac{p_{11}}{p_{11}\,p_{22} - p_{12}^2}\,V_2 \tag{25}$$

In terms of "capacity coefficients" and "mutual capacity coefficients" they take the convenient form

$$Q_1 = C_{11}\,V_1 - C_{12}\,V_2 \tag{26}$$

$$Q_2 = -C_{21}\,V_1 + C_{22}\,V_2 \tag{27}$$

Where C_{11} is the "capacity coefficient" of wire 1 and expressed in terms of dimensions is

$$C_{11} = \frac{25.65 \log \frac{s_{22}}{r_2}}{Z} \tag{28}$$

Z is the denominator common to all the coefficients, namely, C_{11}, C_{12}, C_{21}, and C_{22}. It has a value

$$Z = \left(25.65 \log \frac{s_{11}}{r_1}\right)\left(25.65 \log \frac{s_{22}}{r_2}\right) - \left(25.65 \log \frac{s_{12}}{r_{12}}\right)^2 \tag{29}$$

The "mutual capacity" between conductors $-C_{12}$ is equal to $-C_{21}$

$$-C_{12} = \frac{25.65 \log \frac{s_{12}}{r_{12}}}{Z} \tag{30}$$

and the "capacity coefficient" of wire 2 is

$$C_{22} = \frac{25.65 \log \frac{s_{12}}{r_1}}{Z} \tag{31}$$

If the wires are the same size and the same height above ground then their "capacities coefficients" are identical $C_{11} = C_{22}$ and are identical with the values already calculated by the potential equations.

The "mutual capacity coefficient" for the numerical problem is 3.83 milli-microfarads per mile. It is the same value as found for the capacity of wire 2 toward wire 1 when wire 2 was grounded. But it is entirely different from the capacity of wires 1 to 2 when neither is grounded. The coefficient of "mutual capacity" is always negative. Let us examine what this means. Gradually change V_2 and follow the effect produced.

In equation (**26**) the quantity of electricity Q_1 on wire 1 is diminished in proportion to the " mutual capacity " C_{12} if the potential of wire 2 is of the same sign as V_1. An example has already been worked out, namely when the two wires were connected together *i.e.*, $V_2 = V_1$. At a distance of 48 in. (1.21 m.) apart, wire 1 had a capacity of 8.1 milli-microfarads toward earth whereas when wire 2 was grounded wire 1 had a capacity of 11.9 milli-microfarads total. In other words, the quantity of electricity on wire 1 was diminished by the proportion 11.9 − 8.1 = 3.8 milli-microfarads due to the " mutual capacity coefficient " and making the potential of $V_2 = V_1$. At this potential both wires are charged, say, positively. Now imagine wire 1 and 2 disconnected and the potential of V_2 gradually diminished by changing the potential of the source. As this process takes place Q_1 increases because the subtraction effect of the " Mutual capacity coefficient " in equation (**26**) is decreasing. At the same time the quantity of electricity on wire 2 is diminishing. This charge will reach zero before the potential V_2 equals zero. It will in fact take place when $C_{22}\, V_2 = C_{12}\, V_1$

$$V_2 = \frac{C_{12}}{C_{22}}\ V_1 = \frac{3.8}{11.9}\ V_1 = 0.32\ V_1$$

As V_2 decreases still further toward zero the quantity on wire 2, namely Q_2, changes sign and becomes negative. When V_2 reaches zero then the subtraction factor involving the " coefficient " of mutual capacity in equation (**26**) disappears.

If now the potential V_2 of wire 2 is made negative then the factor containing the " mutual capacity coefficient " in equation (**26**) becomes positive and a still further quantity is now added to wire 1 by the " mutual capacity ". The quantity on wire 2, already turned negative, continues to increase in negative value with the change of potential.

From this cycle of change it is seen that the total capacity may be the sum or difference of the " capacity and mutual capacity coefficients," or it may be equal to the " capacity coefficient " itself according to the sign and value of the potential associated with the coefficient of " mutual capacity." There is less possibility of an error in signs if the total capacity is solved directly from the equations of potential coefficients as used by the writer.

Problem 6. Effect of overhead grounded wire. These

single-phase relations can be extended to three-phase, but before involving the third wire in the circuit, it is important in connection with protection against accidental arcing grounds to note the effect of an overhead grounded wire under two conditions, namely, normal operation and one phase grounded. If the grounded overhead wire were placed at the symmetrical neutral plane it would have no effect on the capacity currents during normal operation. Fig. 17*b* shows the condition chosen. Wire 3 is an overhead grounded wire and wire 2 is grounded.

$$V = \left(25.65 \log \frac{s_{11}}{r_1}\right) Q_1 - \left(25.65 \log \frac{s_{12}}{r_{12}}\right) Q_2 - \left(25.65 \log \frac{s_{13}}{r_{13}}\right) Q_3 \tag{32}$$

$$O = \left(25.65 \log \frac{s_{21}}{r_{21}}\right) Q_1 - \left(25.65 \log \frac{s_{22}}{r_2}\right) Q_2 - \left(25.65 \log \frac{s_{23}}{r_{23}}\right) Q_3 \tag{33}$$

$$O = \left(25.65 \log \frac{s_{31}}{r_{31}}\right) Q_1 - \left(25.65 \log \frac{s_{32}}{r_{32}}\right) Q_2 - \left(25.65 \log \frac{s_{33}}{r_3}\right) Q_3 \tag{34}$$

$$V = p_{11} Q_1 - p_{12} Q_2 - p_{13} Q_3 \tag{35}$$

$$O = p_{12} Q_1 - p_{22} Q_2 - p_{23} Q_3 \tag{36}$$

$$O = p_{13} Q_1 - p_{23} Q_2 - p_{33} Q_3 \tag{37}$$

The solution of equations (35),(36) and (37) gives

$$V = \left[p_{11} - \frac{p_{12}^2}{p_{22}} + \frac{p_{12}\ p_{23}}{p_{22}} \left(\frac{p_{13}\ p_{22} - p_{12}\ p_{23}}{p_{33}\ p_{22} - p_{23}^2}\right) - p_{13} \left(\frac{p_{13}\ p_{22} - p_{12}\ p_{23}}{p_{33}\ p_{22} - p_{23}^2}\right)\right] Q_1 \tag{38}$$

This equation will give the value of capacity for wire 1 but since we desire not hair splitting refinements but just the general effect, a very approximate solution can be obtained easier by certain assumptions.

Approximately:

$$p_{11} = p_{22} = p_{33} \tag{39}$$

$$p_{12} = p_{23} \doteq p_{13} \tag{40}$$

Substituting these values,

$$V=\left[p_{11}-\frac{p_{12}^2}{p_{11}}+\frac{p_{12}^2}{p_{11}}\left(\frac{p_{12}\,p_{11}-p_{12}^2}{p_{11}^2-p_{12}^2}\right)-p_{12}\left(\frac{p_{12}\,p_{11}-p_{12}^2}{p_{11}^2-p_{12}^2}\right)\right]Q_1 \tag{41}$$

$$p_{11}=25.65\log\frac{720}{0.1624}=94.6 \tag{42}$$

$$p_{12}=25.65\log\frac{720}{48}=30.16 \tag{43}$$

$$V=80\,Q_1$$
$$C_1=0.0125$$

With wire 2 only grounded the capacity of wire 1 was 11.9 milli-microfarads. Therefore the increase due to the presence of the ground wire is 0.6 milli-microfarads, an increase of only 5 per cent.

A more important question to answer is, how much does the overhead grounded wire relieve wire 2 of the electrostatic charging current. Since wires 2 and 3 are equidistant from wire 1, $Q_2=Q_3$ approximately, and the ratio $\frac{Q_2+Q_3}{-Q_1}$ is the relative capacity of wires 2 and 3.

From equation (**34**) of the group,

$$p_{23}\,Q_2+p_{33}\,Q_3=p_{13}\,Q_1 \tag{44}$$

$$Q_2=\left(\frac{p_{13}}{p_{23}+p_{33}}\right)Q_1=\left(\frac{30.16}{30.16+94.6}\right)Q_1 \tag{45}$$

$Q_2=25.2$ per cent Q_1 $\qquad C_2=0.00315$
$Q_3=25.2$ per cent Q_1
Q (on ground) $=48.6$ per cent Q_1

Total—100 per cent

The presence of the grounded overhead wire has reduced the charging current on wire 2, when it is grounded, from 32.2 to 25.2 per cent that is, to $78\frac{1}{2}$ per cent of its previous value or $\frac{1}{4}$ of its normal value. Thus the overhead grounded wire increases the range of distance over which a single arcing ground surpressor will protect.

Problem 7. Capacity of wire 1 entirely surrounded.

It is of some interest to figure out the ultimate upper limit of capacity of wire 1 when surrounded by numerous wires grounded and spaced 48 in. (1.21 m.) from wire 1. This is easily done by assuming that the grounded wires form practically a solid tube around wire 1. Then the formula becomes that for a concentric cable.

$$C = \frac{1}{25.65 \log \frac{48}{0.1624}} = \frac{1}{63.4} = .0158 \text{ microfarads per mi.} \quad (46)$$

It is seen at a glance at the equation that the capacity of the concentric condition is just twice the capacity (100 per cent

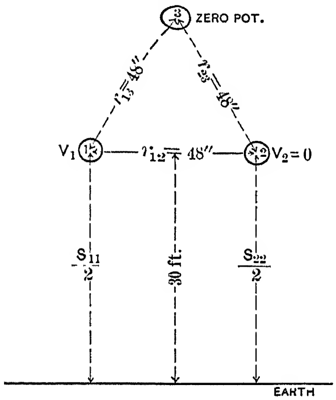


FIG. 17B

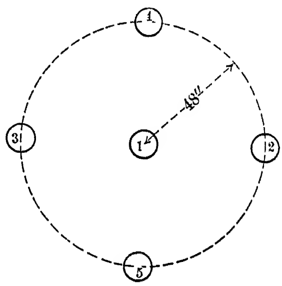


FIG. 17C

increase) of two wires of the same metallic spacing not grounded. The addition of the first few wires distributed on a circumference of 48-in. (1.21-m.) radius rapidly raises the capacity of wire 1 toward its ultimate maximum. Each of the surrounding wires has its capacity lowered by subdivision of the charge.

By dividing the circumference of a 48-in. (1.21-m.) radius into 1870 wires set close together each wire would have a proportional part of the capacity of the central wire giving each a capacity of about 8½ micro-microfarads.

Problem 8. Wire 1 surrounded by four wires symmetrically placed, but not grounded. To give a numerical conception of the foregoing statement and also to show short methods in calculations the problem of Fig. 17*c* is solved:

If wires 2, 3, 4 and 5 are connected together but not grounded what are the capacities? The two equations involving the "potential coefficients" may be written directly:

$$V_1 = p_{11}\,Q_1 - p_{12}\frac{Q_1}{4} - p_{13}\frac{Q_1}{4} - p_{14}\frac{Q_1}{4} - p_{15}\frac{Q_1}{4} \tag{47}$$

$$-\,V_1 = p_{12}\,Q_1 - p_{22}\frac{Q_1}{4} - p_{23}\frac{Q_1}{4} - p_{24}\frac{Q_1}{4} - p_{25}\frac{Q_1}{4} \tag{48}$$

$$\text{Total } V = (p_{11} - p_{12})\,Q_1 - (p_{12} - p_{22})\frac{Q_1}{4} - (p_{13} - p_{23})\frac{Q_1}{4}$$
$$- (p_{14} - p_{24})\frac{Q_1}{4} - (p_{15} - p_{25})\frac{Q_1}{4} \tag{49}$$

$$V = (p_{11} - p_{12})\,Q_1 + (p_{22} + p_{23} + p_{24} + p_{25})\frac{Q_1}{4}$$
$$-(p_{12} + p_{13} + p_{14} + p_{15})\frac{Q_1}{4} \tag{50}$$

Approximately $p_{12} + p_{13} + p_{14} + p_{15} = 4\,p_{12}$ (51)

$$p_{24} + p_{25} = 2\,p_{24} \tag{52}$$

$$p_{11} = p_{22} \tag{53}$$

Collecting these terms:

$$V = \left(1.25\,p_{11} + \frac{p_{23}}{4} + \frac{p_{24}}{2} - 2\,p_{12}\right) Q_1 \tag{54}$$

Approximately the numerical values become:

$$p_{11} = 25.65 \log \frac{720}{0.1624} = 25.65 \times 3.646 = 93.5 \tag{55}$$

$$p_{23} = 25.65 \log \frac{720}{96} = 25.65 \times 0.875 = 22.4 \tag{56}$$

$$p_{24} = 25.65 \log \frac{720}{67.8} = 25.65 \times 1.025 = 26.3 \tag{57}$$

$$p_{12}=25.65 \log \frac{720}{48}=25.65\times 1.176=30.15 \tag{58}$$

$$V=(1.665+5.6+13.15-60_1 3)\, Q_1 \tag{59}$$

$$C_1=\frac{1}{75}=0.01354 \text{ microfarads per mi.} \tag{60}$$

The four wires surrounding wire 1 increase its capacity $\frac{13.54}{7.9}=172$ per cent.

Wire 2 of surrounding wires has its capacity reduced from 7.9 milli-microfarads, when alone, to $\frac{13.54}{4}=3.38$ milli-microfarads when one of four.

Although the foregoing problem is not one likely to be met in practice it is only necessary to ground the surrounding or adjacent wires and the practical condition is reached of one circuit in operation and a parallel circuit on the same pole line grounded while making repairs.

The following table summarizes the numerical results. The height above ground is 30 ft. (9.14 m.) in every case and the distance between No. 0 B. & S. conductors 48 in. (1.21 m.) except in problem 3*a*.

Example	Dist. between wires	Condition	Comparable capacities milli-microfarads				$\frac{Q_2}{Q_1}$	$\frac{Q_g}{Q_1}$
1	48 in.	1 *vs.* 2 neither grounded	1 to 2 7.90	2 to 1 7.9	1 to gr. 0.003	2 to gr. 0.003	1	0
2	"	1 *vs.* 2 and G	1 to 2+G 11.90	2 to 1 3.83	1 to gr. 8.07	—	0.322	0.678
3	"	1 only *vs.* G	1 to G 10.64	—	—	—	0	1
3*a*	10.82 in.	1 *vs.* 2 neither grounded	1 to 2 10.64	2 to 1 10.64	—	—	1	0
4	48 in.	1 and 2 together *vs.* ground	1 to G 8.1	1+2 to G 16.2	—	2 to G 8.1	1	2
6	"	1 *vs.* 2+G+gr. wire	1 to all 12.5	1 to 2 3.15	1 to gr. 6.2		0.25	0.50
7	48 in.	1 *vs.* cyl.	1 to cyl. 15.8	2 to 1 0.008			0.003	—
8	"	1 *vs.* 4 wires no G	1 to all 13.54	1 to 2 3.38			0.25	—

Having gone thus far with nothing but simple problems in sight, the writer doubts the advisability of taking up more space with further calculations. Numerical examples have shown general relations which can be extended to multiple conductors. High accuracy in capacity measurements of transmission lines is quite unnecessary and inconsistent in the light of errors introduced from such causes as harmonics, therefore in solving involved problems it is permissible to assume identities between the logarithms of ratios that are nearly alike. This simplifies complicated relations to such an extent that calculations are readily made. Certain other factors may be eliminated on inspection. For example, a parallel wire with practically zero charge disappears immediately from the equation of capacity of any other conductor. The earth at a total charge of zero affects inappreciably the capacity of a pair of conductors unless the earth forms an appreciable part of the total path of the electrostatic flux; in other words the earth at zero charge total exerts an inappreciable effect unless the two wires are nearer the earth than to each other. The earth when charged, *i.e.*, used as a return conductor, exerts a great influence on the capacity by its large surface. The mutual capacity between the conductor and one other of a surrounding group of wires can be estimated frequently by using a mean logarithmic distance and the concentric cable capacity of the conductor reduced with judgment to correspond to the surrounding condition.

So long as circuits operate normally with their natural neutral undisturbed the capacity and the mutual capacity relations have little vital interest but when an accidental arcing ground occurs these constants may rise suddenly to importance.

One of the important factors in contemplated protective dedevices is this one of mutual interaction of conductors.

Maintenance of the Accidental Arc at the Insulator. There are no data on the relations of voltage, current and arc length for accidental arcs on insulators. The dangers to insulation on a system in making such tests practically, are so great that operating engineers can not undertake the risk for the personal value of the results. The principal value of the results lies in their use to design an insulator which will extinguish its own grounding current. Such a thing is practicable on short lines. The solution of the problem of the relations of arc length to voltage, length of line, etc., involves a discussion of a number of factors relative to internal surges. The matter of internal surges is

too extensive and too involved to find a place as part of this paper. Certain relations of arc current and potential, however, may be pointed out. Oscillographic studies have been made by a number of scientists on arcs for illuminating purposes. These arcs are maintained under stable conditions. Stable conditions involve arcs of comparatively short lengths in inductive circuits where the current lags more or less behind the impressed e.m.f. In a circuit where the capacity predominates the arc current reduces to zero before the potential and is not reëstablished in the opposite direction until the potential passes through zero and rises sufficient to reëstablish the arc. This interval between the extinction and relighting of the arc gives it a chance to cool and deionize. The potential to strike the arc across this space is frequently the spark potential of the gap. In other words, in order to maintain an arc in a condenser circuit, the arc length is frequently limited to the spark length. Furthermore, the arc is usually unstable even during a half cycle, when the potential is in one direction. As the voltage rises there is a spark, a sudden rush of current attended with more or less oscillations, and, since the condenser becomes charged, an extinction of the arc. This may be repeated any number of times during a half cycle of the generator, according to the local conditions.

If the grounding current of a line were purely capacity current most of the arcing grounds would be extinguished by the natural conditions. The inductance of the line and, since the same current as the current to ground must pass to the not-grounded phases through the coils of the generator and transformers, the inductance of the apparatus is involved. The presence of this inductance aids in maintaining a grounding arc although it is insufficient to produce a lagging current.

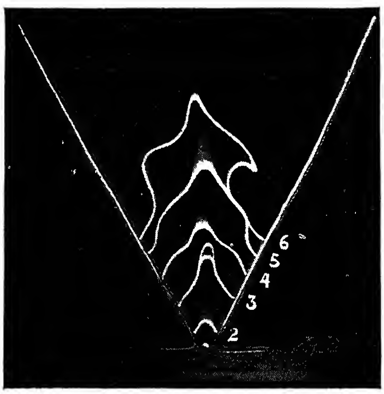
Some accidental flashes over single insulators are extinguished without causing a noticeable disturbance. These transient grounds have been noted and recorded on a lightning arrester discharge recorder but not actually observed.

From our knowledge of the conditions two possible explanations of the extinction of the arc may be made. First, the spark around the insulator may take place at an instant when the generator voltage is either decreasing or near zero. Second, the spark may take place on the lea side of an insulator and a favorable wind at right angles to the line whip out the arc.

When all these factors favorable to the extinguishment of the

grounding arc are considered and there is added to this a metallic ground at the protector which maintains the generator end of the phase at constant zero potential and is in parallel with the arc with the intervention only of the line inductance, there is little or no chance of maintaining an arcing ground even at great distances from the protector.

Tests of Arc Lengths, Current, and Potential at Variable Power Factors. Long arcs by reason of their temperature tend to rise. They are wafted about by local air currents and frequently loop back and short circuit a part of the arc length. Some times an arc is entirely broken by a local air current and reëstablished by a spark in the succeeding half-cycle of the generator wave. These variations make it impossible to study an arc by means



This illustration shows six exposures. Each exposure had a duration of one milli-second. The time between exposures was eight cycles (0.13 sec.). The first exposure took place, as shown in Fig. 18*b*, four cycles after the current started. The arc was started by means of small wires projecting from each horn and, as the photograph plainly shows, the arc had not yet burned the fuse wire back to the horns. The third exposure shows the arc in the act of short circuiting a small upper loop. While this shortening took place at the highest part of the arc the other parts were being lengthened so that it happened that no appreciable change took place in the potential wave.

FIG. 18A

of the usual ammeters and voltmeters. By a combination of the oscillograph, photographic plates and revolving discs it is practicable to obtain instantaneous records which can be examined and measured at leisure. Some of the preliminary studies of long arcs are given herewith. These complicated tests were carried out by Mr. H. E. Nichols. A camera was placed behind a revolving disc which contained a hole to give successive exposures. A contacting device connected in circuit with one of the oscillographic vibrators makes the vibrator deflect every time an exposure of the camera is made. The arc length can be measured on the photograph and the simultaneous current and voltage at each exposure can be taken from the oscillogram since the other two vibrators were used to record the curves of current

and voltage of the arc. It is then necessary to start the exposure on the oscillographic film and immediately afterwards the arc at the horns. Sometimes the arc was started by means of a static spark properly timed and at other times by means of a shortened gap. This latter consists in nearly closing the gap by means of a fine wire (3 mil. diameter in these tests). It is better thus to bridge only a part of the gap, rather than all of it with a fuse, as the arc will burn the fuse wire out of the way quicker than it can otherwise melt and blow it. This is important where small currents are involved and rapid action necessary.

A complete test consists of three parts, at least—namely, the photograph of the successive positions of the arc, the corresponding oscillogram, and the tabulated values or curves of arc

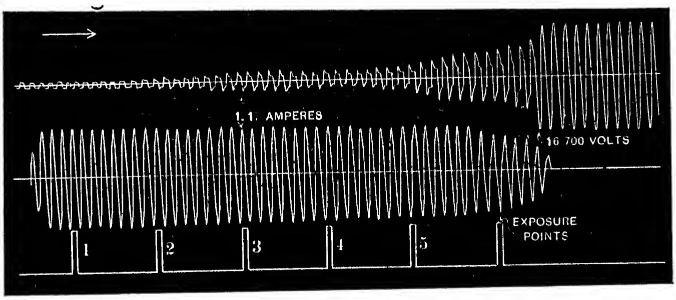


FIG. 18B

The lower record shows the instant of exposure of the photographs of arcs, the middle record the current in the arc, and the upper record the potential across the arc. The transformer feeds a condenser and, therefore, the current leads the e.m.f. by 90 deg. The final values of current show that the arc ceases very gradually. The arc lengthens and cools, takes more voltage and decreases the current without any abrupt changes.

length, versus potential or current. Since the study is being made with alternating currents there is some question concerning the proper expression for the voltage and current. Shall it be the effective value, the initial maximum, the usual value after the arc is established, or one of the several other expressions? The initial peak value of potential across the arc is important because it determines whether the arc can be relighted or not by the circuit. The more time the arc has to cool between half cycles of the generator wave the more the potential required to again establish the arc with the current in the opposite direction. In all these arcs there is usually a period about midway in the half-cycle when the current and potential hold briefly at nearly a constant value. These readings are valuable in giving information of the conditions of an established arc. The peak potential

and the usual potential or potential of the established arc are plotted in the tests herewith reproduced.

Test No. 1. This test consists of four parts, Figs. 18*a*, 18*b*, 18*c*, 18*d*, *viz.*, photograph of the arcs on the horns, one oscillogram corresponding thereto, one oscillogram taken subsequently with the film at higher speed to show the detailed forms of waves of current and potential, and curves of arc length versus potentials and current. Comments and further details are given under each figure.

Test No. 2. Figs. 18*e*, 18*f*, 18*g* and 18*h*. This test differs from the previous test in that the circuit has high inductance and consequently a large angle of lag, of current behind the

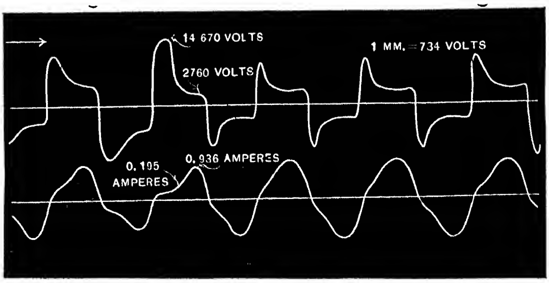


FIG. 18C

The current and potential of an arc in series with the same condenser. The last three cycles of potential show the normal form of potential across the arc. The first and second cycle are distorted by the effect of an air current on the arc which nearly extinguished it. In the second cycle the potential remained high for a proportionately long time before the current could get above 0.2 amperes. Apparently this particular arc had an unstable value at 0.2 amperes. Compare it to the stable condition of current shown in the succeeding cycles. After the third exposure there is evidence in the potential wave that the arc resistance decreased due probably to shortening. The position of the arc relative to the plane of the horns is not shown in the illustration (18*a*) and, therefore, the arc length is of somewhat indefinite value.

impressed e.m.f. The e.m.f. across the arc is in phase with the current. The wave shape of current is different and the e.m.f. across the arc correspondingly changed.

General Discussion of the Protective Problems

With the assurance that the new apparatus for the protection against an accidental grounded phase will do away with a large percentage of line troubles due to lightning, it seems worth while to make a general survey to determine the nature of the phenomena to be met and the degree of solution already achieved in the vital problem of absolute continuity of service.

Two New Terms to Express Conditions of Protection. In the discussion of phenomena relating to line protection, it has

been necessary to coin terms to briefly express what would otherwise require a sentence or paragraph. Two of these terms are tentatively offered as follows:

Super-Spark Potential. Dielectric spark lag is a condition that has been known for several years. There is always this interval after potential is applied before the spark forms. During this period ionization of the gap takes place. If the applied potential is just equal to the spark potential it requires a considerable interval of time to ionize the gap. In one particular case described at the Jefferson meeting it required several seconds. As the applied potential is increased above the long-time-

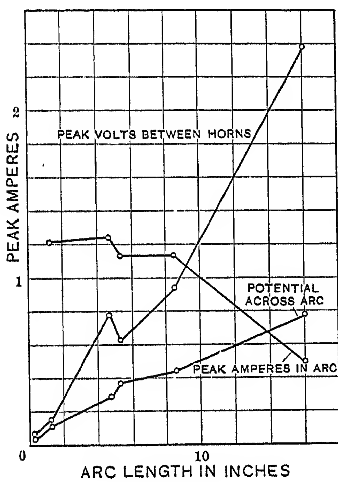


FIG. 18D

Curves of arc length versus current and potentials. Up to 10 in. the current preserves a nearly constant value of 1.2 amperes and then drops. Both the peak potential and the potential of the stable arc are nearly proportional to the arc length.

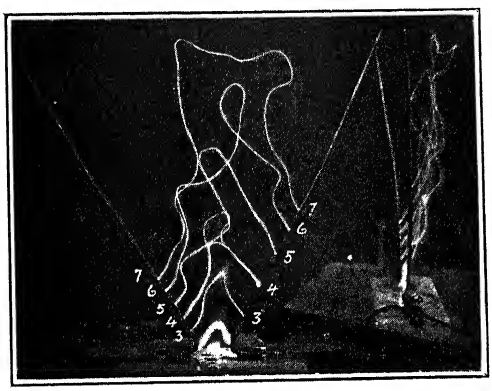
applied-spark potential the spark lag decreases. This potential in excess of the spark potential is herein designated as the super-spark-potential. So far as measured, the relation between the super-spark-potential and the dielectric-spark-lag is hyperbolic. As a numerical illustration, when the super-spark-potential was 10 per cent above the spark potential, the dielectric spark lag was 200 milliseconds. When it was 100 per cent above the spark potential, *i.e.*, double potential, the spark lag was reduced to five milliseconds.

Dielectric-spark-lag should be distinguished from the lag in the formation of an arc around an insulator (or other device that involves corona streamers) when a spark potential at a

normal frequency is applied. This distinction is made farther on.

The second new term that is used herein is bolt-peak, or sometimes, bolt-point.

Bolt-Peak. An overhanging thundercloud induces static electricity on the line which is graded in density according to the nearness of the point on the line to the charge in the cloud. The point of maximum charge is designated as the bolt-peak. When the bolt of lightning discharges to ground near the line, the bolt-peak on the line exists at a point having the shortest perpendicular distance to the path of the lightning. If the path of the lightning is inclined to the line the bolt-peak on the line may not be the point on the line nearest the point on the earth struck by



Seven exposures of arc rising on horns. Exposure four shows a loop of arc short circuiting on itself at the highest point. Due to an accidental air current the arc rose better on one horn than on the other.

At the right is shown the arcs in the plane of the horns. This is taken by the use of a mirror at a 45-deg. angle to the camera. The photograph shows that the arcs are practically in the same place and measurements of the lengths on the front view side will be correct.

FIG. 18E

the lightning bolt, although it usually is. If the line itself is struck the bolt-peak naturally occurs at that point.

Nature of Surges on Overhead Lines. Separating the internal surges in apparatus from the surges in the line, it is convenient to treat line surges under three heads, namely, *lightning*, *resonance*, and *stationary waves*. The most frequent cause of trouble is lightning which is the subject of the following treatment.

Lightning Induction. Electrostatic induction on a transmission line is of a fairly uniform nature, although the induction differs in intensity from a negligible value up to a direct stroke coming from a large cloud or group of clouds. Not from actual observation, but from our knowledge of electrostatics, the following well known theory of the mechanism of charge and discharge has been formulated.

A charged cloud or its equivalent is in a position above the line. By electrostatic induction a charge is drawn onto the line because the line is nearer the cloud than the ground is. Assuming the case of a cloud nearly overhead and discharging to

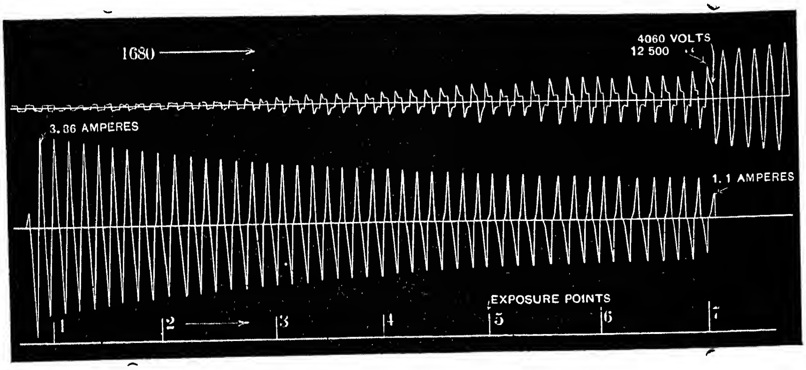


FIG. 18F

This oscillogram of current and potential of the arcs is very similar to the previous case. The current starts higher, at 3.86 amperes, and gradually decreases—this, however, results from the regulation of the circuit.

A very important phenomenon in the theory of long arcs is illustrated during the last cycle of current. In the cycle before the last the potential rises to 12,500 volts and the current to 1.1 amperes. This half cycle wave of voltage shows the characteristic form for the potential drop across an arc but the following half-cycle does not, although there is a current in the arc. The voltage rises to 15,900 volts but it causes only a small current which has the nature of a leakage current. This current is insufficient to give the arc its usual "negative characteristics" and yet enough to prevent the gases from being entirely deionized.

During this brief period the photographic record does not show what changes are taking place in the arc length. However, some important information of the arc in its last flickers may be obtained from a tabulation of currents and potentials of the oscillogram. Starting with the first cycle after the extinction of the arc and working backward, in successive half-cycles, the difference of potential is 1,700 volts at zero current, 15,900 volts at 0.22 amperes, 12,500 volts at 1.1 amperes, 10,300 volts at 1.6 amperes, and 10,000 at 1.7 amperes. Up to the value of 2 amperes, the equation of these points follows a straight line

$$V = 17{,}000 - 8{,}210\, I$$

The equation cannot possibly hold true much beyond the limit given.

It is probable that during these last two cycles of current the arc does not change much in length. On this assumption that the potential of the dying arc varies directly with the product of current times resistance the resistance per unit length of the arc may be found. Using simultaneous values the potential was about 4,500 volts when the current was 1.1 amperes. This gives a resistance of 4,100 ohms total (180 ohms per inch, 2,160 ohms per ft., 71 ohms per cm.). At the peak value of 12,500 volts on the same half-cycle the simultaneous current was 0.15 amperes which gives a resistance of 83,000 ohms total (3,600 ohms per inch, 43,200 ohms per ft., 1,430 ohms per cm.). Calculations from the last half cycle of current at 0.22 amperes gives 73,000 ohms total (3,200 ohms per inch, 38,400 per ft., 1,250 ohms per cm.)

A useful value of resistance may be found by using the peak potential and peak current in each half cycle. These values are not simultaneous but they give an average resistance during a half cycle. The corresponding values are as follows: 12,500 volts, 1.1 amperes and 11,400 ohms total; 10,300 volts 1.6 amperes, and 6,400 ohms total; 10,000 volts, 1.7 amperes, and 5,900 ohms total. These tests, as already stated are preliminary and due to the methods of tests are only roughly approximate.

ground near but not onto the lines, the fixed charge on the lines at the moment of cloud discharge will be very much concentrated. Soon after it is freed it tends to spread over the lines and distribute itself uniformly. There is the corresponding charge of

the opposite sign on the ground underneath. In order to move a charge of electricity, current, involving electromagnetic energy, must be built up; in other words the moving charge meets the self-induction of the line wire. Therefore the localized potential

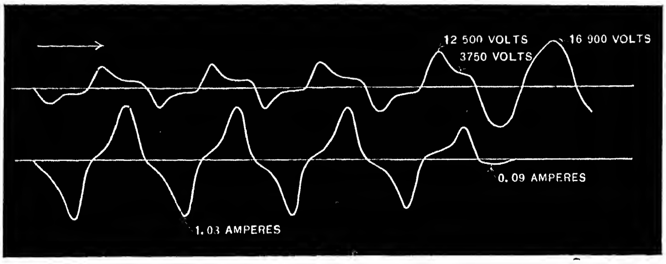


FIG. 18G

Subsequent high speed oscillogram of arc rising on horns. Details of the shapes of the waves are evident. The same phenomenon of final current is again reproduced as in Fig. 18*f*. This current has a value of 0.09 amperes at 16,000 volts. The length of arc was not photographed but it is presumably about the same as the one photographed in Fig. 18*f*, *viz.*, about 23 in. (58.3 cm.) long.

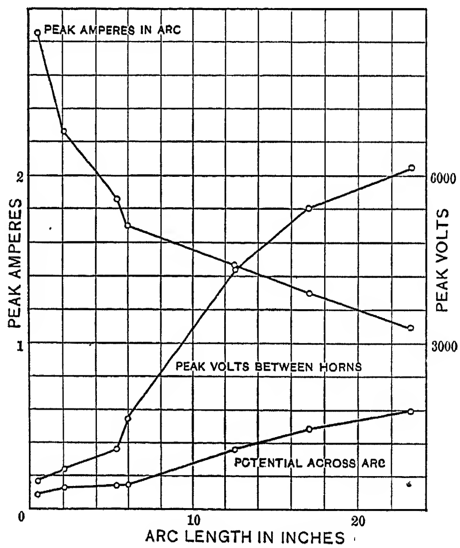


FIG. 18H

Arc length versus current and difference of potential. Since all three factors ,*viz.*, length, current and potential varied, it is not possible to deduce the equation for long arcs from it. However, it gives the exact phenomena taking place in horn gaps in series circuit.

will be held momentarily on the insulators. This much of the theory has been repeated a number of times.

Rapid Electrostatic Induction Causing Heavy Currents on the Line During Cloud Discharge. In addition to the foregoing

there is a phenomenon taking place during vertical strokes not yet emphasized. At the instant that the charge is set free on the line there is reason to state that the charge is not in a quiescent condition.

Figs. 19 and 20 are attempts to illustrate what the theory leads us to believe takes place. Fig. 19 illustrates the quiescent condition. Fig. 20 is the active condition. While the bolt of ightning is forming, the rush of static from opposite directions

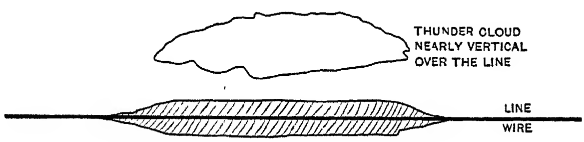


FIG. 19.—Thunder cloud nearly vertical over line

magnifies the potential at the bolt-point on the line. Furthermore, the time of application of high potential is increased, due to the necessity of doubly transforming the electromagnetic energy of the current in order to reverse it in direction, and by its outward flow from the bolt-point relieve the strain. If the potential is high enough and the time of application long enough, a " spill-over " on the insulator about the bolt point will take place. If the bolt from the cloud strikes near the line the bolt-

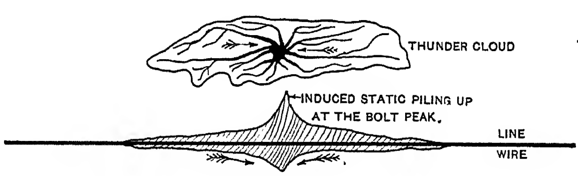


FIG. 20.—Thunder cloud discharging

peak may send out a streamer to the main bolt, which is, in effect, a side-stroke to the line. This theory is given to lead up to a discussion of the use of arresters to protect lines.

Possibility of Using Lightning Arresters to Protect Against the Bolt-Peak. In the foregoing theory it is indicated how the induction on the line from a cloud may extend over as much as a mile, yet when the lightning bolt takes place it may cause a bolt-peak on the line confined to a very short length. All the experience with broken insulators and damaged poles show a

narrow localization of the trouble on one to four poles, the latter only for wooden poles and direct strokes on the line. This will be discussed further, under direct strokes. It is conclusive that in order to be effective, lightning arresters to protect the line against the bolt-peaks of static induction would have to be placed with comparatively short distances between them. What this spacing should be can only be guessed at.

Some observations lead one to say that it would be necessary to have an arrester at every tower or perhaps every other tower. Insulators have been known to spark over two towers away from a protected insulator. The danger is relative, being controlled by the relation of the protective value of the apparatus at one insulator to the spark potential of insulators on any adjacent tower. The better the insulator, the greater the possibility of protecting at some distance away.

It is doubtful if any known arrester situated on the line at some distance from the bolt-peak would be able to trap this moving charge as it rushed by in the travel toward the bolt-peak. This doubt comes from a consideration of the dielectric-spark-lag of any gap of an arrester and the velocity of movement of the charge along the line. With an assumed distance of 1000 ft. (304 m.) between the arrester and the *bolt-point* and the charge of electricity rushing toward the bolt-point at the rate of 180,000 miles (590,550 km). per second, the dielectric-spark-lag of the arrester would have to have the impossible value of less than 1/900 of a micro-second. Since the gap of an arrester so applied should not, for other reasons, be set close to line potential there will not be a great difference in the dielectric-spark-lag of the arrester and the usual insulator. In conclusion both operating and laboratory experience to date indicate the use of lightning arresters in reasonable numbers along the line would not give a protective value sufficient to warrant their installation. The cost of a lightning arrester varies directly with the voltage and it would require more conviction than the evidence now in hand gives, to warrant the expense.

Trolley Line Arresters. This discussion does not cover the case of lightning arresters, along a trolley line. Lightning arresters along a trolley circuit are in reality, to assist in the protection of car apparatus. That they protect the line also, to a certain extent, is an incidental matter. Furthermore the circuit voltage being low the cost of the arrester is not such as to make its use in considerable numbers along the line prohibitive.

Why "Spill-overs" Occur Usually on Only One Insulator. With the foregoing theory of the static charge on the line in mind, an explanation of the frequent limitation of failure to one insulator can be added. In this theory any high frequency which may be superimposed on the charge when it is freed by the cloud discharge will be neglected. At the instant that the charges on the several wires of the transmission line are freed, there is probably only a slight inequality in the potential of the lightning on the several wires or phases. Due, however, to this inequality in the lightning potential and also to the variable values of dynamic potential on each phase at any instant, the conditions frequently favor the failure of only one insulator. No doubt in some cases variations in the dielectric strength of the insulators may also play a part.

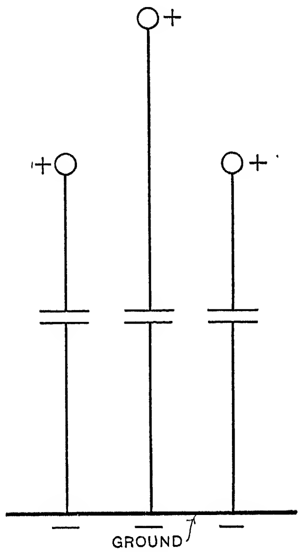


FIG. 21.—Capacity of lines to ground for lightning

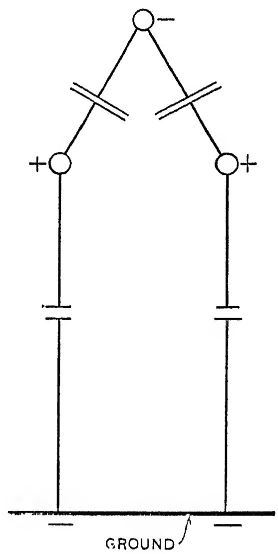


FIG. 22.—Capacity of lines to ground, one wire grounded

In order to show the effects of the instantaneous values of dynamic potential on the spill-overs of insulators, two numerical problems are chosen; one of these problems shows the extreme conditions favoring the failure of one insulator, and the other problem shows the extreme condition favoring the failure of two insulators simultaneously on different phases. In a circuit in which 60 kv. effective is impressed, the peak potential of the

generator wave is 49 kv. to ground. Choosing an instant when phase No. 1 is zero, phase No. 2 has a negative potential of 43 kv. to ground at that instant and phase No. 3 of 43 kv. positive. If at this instant a lightning potential of 200 kv is impressed on the line, the potentials of the generator waves would be added or subtracted to this lightning potential. Since the lightning potential exists between lines and grounds, the addition must be made to the instantaneous values of the " Y " potentials of the generator. Phase No. 1 being at zero, the total potential will be 200 kv. Phase No. 2 being at negative potential, will have a value of 200 kv. minus 43 kv. = 157 kv. Phase No. 3 being positive, will add directly to the lightning potential giving 243 kv. The three phases then have impressed upon them 200, 157 and 243 kv. This condition evidently favors the failure of the insulator on phase No. 3.

As an illustration of the condition favoring the failure of two insulators the time in the cycle of the generator is chosen when two phases have equal potentials of the same sign. This occurs when one phase is at its maximum potential to ground, *i.e.*, 49 kv. There will be two sets of resulting potentials from the superimposed line potential according to whether the signs are taken positive or negative. If the sign of the maximum generator potential is taken negative when the lightning is positive, the potentials on the three phases will be 151, 224.5 and 224.5 kv. In this case, phase No. 2 and phase No. 3 will have an equal tendency to spark over to ground. Assuming the condition of opposite signs between the lightning and generator potential, the potentials will be 243, 175.5, and 175.5 kv. Considering the elements of chance, the conditions favor very much the failure of a single insulator. This statement will be evident if one considers that at the time two phases have equal potentials, they are both changing their potentials at a rapid rate in the opposite directions. Even for this instant, the chances are one in two that the lightning will have the opposite polarity and not be additive.

Turning now to the lightning charges on the lines, there appears instantly at the time of a cloud discharge two effects which influence the potentials of the different phases. One of these effects is electrostatic and the other electromagnetic.

In releasing the potential strain on one wire relative to ground, the strain on the other wires is reduced, although there may be no change in the charges on the other wires. This is due to the

change in static capacity of the system. Before the single insulator breaks down all the wires are acting as one plate of a condenser with the ground as the other plate. (Fig. 21.) On account of the great distance to the ground the static capacity of the wires is relatively small. As soon as a single conductor is grounded (Fig. 22) it becomes oppositely charged and the static capacity of each of the other conductors is relatively increased by the proximity of this grounded conductor. The same charge in a larger static capacity lowers the voltage according to the fundamental equation $V = \frac{Q}{C}$.

The lowering of the voltage retards the spark by the value represented on the hyperbolic curve of dielectric-spark-lag versus time. During this added interval the static charges left on the wires have time to spread in both directions along the wires and thereby lower the potential strains still further. The

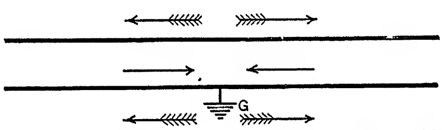


FIG. 23.—Electromagnetic induction between lines

capacity of one conductor of three at six feet (1.8 m.) apart used as one plate of a condenser, with the ground 30 ft. (9 m.) away as the other, is 0.0069 microfarads. This same conductor grounded gives an added capacity to each of the other conductors of 0.0025 microfarads or a total increase of 143 per cent.

The electromagnetic effect is much greater apparently than the electrostatic effect of the change of capacity.

With the middle wire grounded as shown in Fig. 23 there will be a rush of current toward the grounded point. These two currents represented by the non-feathered arrows will induce extra electromotive forces in the adjacent wires which give an added impulse to relieve the potential strains on the other wires. The induced potential is represented by the feathered arrows.

Apparently these two factors are so important that in the systems studied the majority of insulator "spill-overs" are limited to one insulator. However it is evident that the phenomenon of reduced voltage, due to these factors, has its limitations and more than one insulator may be caused to fail.

Numerical Conceptions of the Factors of Induced Lightning. There is so frequently formed a misconception of the functions of a lightning arrester in discharging lightning and dynamic currents that the following calculations are given to aid in defining the requirements. Especially in foreign installation has it been brought many times to the writer's attention that certain type of arresters were operating satisfactorily, the judgment being based entirely either on the number of times the arrester had sparked or, on the brilliancy of the spark. Neither of these qualities are *necessarily* a measure of the value of the arrester. High resistance arresters with small series gaps spark easily without giving much protection. Arresters allowing considerable dynamic to follow may give both brilliancy of spark and noise in discharge and yet not be very effective.

The following approximate assumptions are made: One mile (1.6 km.) of line having about 0.012 microfarads capacity to an overhead grounded wire is charged to 100,000 volts potential by lightning.

In this charge the quantity of electricity is 0.0012 coulombs and the energy 60 joules.

This energy would light a 50-lamp arc circuit for less than 0.004 second.

It would light a 16 c.p. incandescent lamp for about one second.

At 10 cents per kw-hr. it would cost 0.000016 cent.

It would raise one pound (0.45 kg.) weight about 40 ft. (6 m.).

The quantity 0.0012 coulombs traveling along a line at its natural rate of speed, 180,000 miles (590,550 km.) per second, represents a current wave of about 200 amperes and would have to be discharged at that rate if the potential at the end of the line is to be kept down.

If the charge oscillates at 10,000 cycles per second it represents a current of about 12 amperes.

If allowed to discharge at the rate of one-half ampere it would require 0.001 second to reduce the potential to about half, *i.e.*, 50,000 volts; if at the rate of 600 amperes the time would be reduced to 0.000001 second.

When this energy of discharge is transformed into chemical energy its relative value sinks into still further insignificance. For example, it would deposit only 0.0000013 grams of silver. For the disassociation of aluminum it would give a number of the same order.

If all the energy were dissipated in heat in the aluminum

arrester instead of being absorbed mostly in chemical action, it would raise one gallon (3.8 liters) of electrolyte only 0.0037 deg. cent.

These quantities are quite small, still it takes much less energy to puncture a small hole in any ordinary insulation. If the charge on the line were at a million volts, the foregoing values would still be small.

If a good lightning arrester with a high rate of discharge, a large electrochemical absorption capacity, a large heat capacity, and taking practically no dynamic current, makes no fuss or noise in the ordinary discharge, or does not permit of a large puncture of a paper in a series gap, it is no indication that the arrester is not performing its function of protecting.

Some Observations on Direct Strokes. There is a possible gradual increase in intensity of lightning potential on a line varying from a negligible impulse up to the irresistable lightning bolt derived from a dozen large clouds. Theory and observation, however, indicate that there is, in general, a clear cut demarkation between the induced and direct strokes. Unless there is some high conductor in the neighborhood of a line, the conditions of cloud discharge, the height of the line, and the good horizontal conductivity of the wires favor either striking the line or striking at some distance from it. The factors of suddenness of formation of the thunder clouds, the particular localization of cold air coming in contact with jets or spouts of moist warm air, relative distances, and so forth have no doubt a strong bearing on the subject. The theories of cloud formation given by Dr. Steinmetz a number of years ago satisfactorily explains many of the various phenomena of direct strokes. This part of the subject is beyond the scope of this article.

It is of scientific interest to know how close to a line a lightning bolt may strike and cause a certain dangerous rise of potential, and how this potential is raised as a side-stroke from the main discharge, may lick out and touch the line, and how these side-strokes may vary in volume from a tiny static discharge up to the great volume of a direct bolt.

It is of practical value to determine in general; first, the minimum distance that may exist between the main discharge and the bolt peak without causing a spill-over on any particular type of insulator; second, in the next step in severity, to determine the minimum distance between the main stroke and the bolt-peak on the line that may exist without causing insulators

on two separate phases to spill-over simultaneously and cause a short-circuit of the power; third, to determine if it is practicable ever by means of lightning rods extending above the poles or towers to conduct the majority of lightning bolts down through lines of reasonable spacing, without causing a spill-over of the power.

These broad engineering problems of protection must be solved before the natural growth of electrical power transmission can advance much further toward perfect continuity. Each year an advance is made in some of the more obvious problems of protection. The problem of protection against lightning in its last stage—that is, protection against a direct stroke—is not the manufacturer's problem alone. There is nothing obvious in protective apparatus to sell and, therefore, the manufacturer's interest must be simply to widen the field of use of transmission apparatus by giving immunity from trouble. No single transmission company can afford to spend the money and time necessary to solve these problems, each can help by making systematic observations. Judging from the present outlook, however, no rapid advance will be made until the matter is taken up formally and systematically with the efforts centralized on some few particularly favorable systems, the expense and work being shared possibly by an association of transmission companies, and the manufacturers of electrical apparatus. The coöperation of the U. S. Weather Bureau, the Carnegie Institute, and such other societies interested would be of value.

Some of the Effects of Direct Strokes. Some of the effects of direct strokes observed are given as follows: Where direct strokes occur, a short-circuit of the power usually accompanies. Insulators are usually shattered. If the direct stroke did not do it, the power arc would; it is thus impossible to attribute the cause entirely to the lightning. On the metal tower lines or where the insulator pins are grounded, the arcs from direct strokes are confined usually to one tower. When, however, wooden cross arms and wooden poles or towers without metal grounding wires are used the direct bolt usually spreads over several poles or towers. The difference in these actions is due to the fact that the sparking distance for the case of the grounded pin is limited to the arcing distance of the insulator, a distance of the order of one foot (0.3 m.). The spark takes place before the charge can spread horizontally along the line. When, however, the sparking distance is 30 ft (9 m.) or more down the poles

the charge has time to spread horizontally along the line (or perhaps the main bolt forks) and this divides between two or more poles or non-conducting supports. There is less liability of a direct bolt striking a line separated from the ground by wooden poles without lightning conductors but when such a line is struck the damage to the wooden poles frequently requires renewals. Other things being equal, the transmission line is probably somewhat more liable to be struck than trees or other poorly conducting objects near and just as high because of the possibility of the electricity gathering horizontally along the wires and by the concentration of potential this should favor the formation of discharge from this point. In the case of the metal towers, which act as lightning conductors, there is, I believe, much to favor this path for the lightning bolt. Only two instances are known of lightning striking through the lines and burning them off midway between poles, without damaging the poles. It is probable that these were very sudden heavy strokes.

Where lightning will strike, has been the subject of speculation by a number of scientists. Dr. Steinmetz has expressed the opinion that the charge follows the paths in the atmosphere that are under the greatest stress—this stress not being produced by the charges on a definite cloud and earth but by the accumulated charges at every point in the atmosphere.

From the meagre data at hand and from the most plausible speculations the path of lightning will be decided by such factors as:

1. The charges in the clouds.
2. The ionization of the intervening layers.
3. The shortest path of the stroke.

This ionization of intervening layers of atmosphere depends upon such factors as moisture, temperature changes, and unknown sources. The effect of the local stresses on the path probably depends greatly on accidental conditions of air currents, funnels, etc.

It seems reasonable, however, to assume that there are certain layers of air not locally ionized but put under heavy static strain by the accumulation of electricity in the clouds and, therefore, the effect of the shortest distance between points must come into play. Everything else being equal, the highest conducting point must be struck by lightning.

It seems probable that some other factors bearing on the direction of lightning strokes may later be recognized. Using

the information and theory at hand it is the relative prominence of the second and third factors, namely, local ionization in the atmosphere versus the shortest path, which are of vital interest in the design of a circuit to be absolutely immune to lightning. The answer must be found to the question, what must be the spacing and height of the overhead grounded wires to prevent the local ionization between lines directing a lightning bolt on to the transmission wires?

If there is a wind it is inconceivable that air near the earth could be very highly ionized. It is constantly being rolled over in contact with the earth which would tend to keep the potential down and somewhat uniformly distributed.

If there is no wind and the atmosphere between widely separated overhead grounded wires becomes charged locally to a high potential there is the electrostatic force tending to draw the charges in the free moving atmosphere toward the grounded wires and thus discharge it. So far as these theories can be depended on they show that the law of the shortest path is the predominant factor near the overhead grounded wires. The spacing between the protecting grounded wires and the power wires must be determined. This distance, to be safe to the power wires, is to be determined by taking into account the type and spark potential of the insulators, also the corona losses from the power wires.

An endeavor has been made in the foregoing paragraphs to present the general nature of the problem of protection of transmission lines from lightning. In the extreme, there is at present no way of preventing some lightning affecting the operation of a transmission circuit. And there has been little done to minimize the destructive effects of direct bolts. There is, however, something that can be done to minimize the effects of light strokes and induced strokes, and much can be done to prevent damage to the circuits and avoid interruptions of service.

What has Been Done to Protect Lines. First. The overhead grounded wire has been used. Great stress has been laid on the electrostatic screening by the overhead wire but the electromagnetic induction has been somewhat lost sight of. For example the practice of grounding every five poles on wooden pole lines may not be sufficiently frequent. A single overhead wire does not give perfect screening from electrostatic cloud induction. If, moreover, this screening charge must run a considerable distance to get to earth it may induce nearly full

potential, by electromagnetic induction, on the power wires. To endeavor to get concrete ideas on this value experiments were made in imitation of the line conditions.

The relations of the overhead grounded wire and a transmission wire are shown diagrammatically in Fig. 24. At the instant the electrostatic lightning charge is freed on the overhead grounded wire, the charge divides and rushes toward the nearest grounded point as shown by the arrows

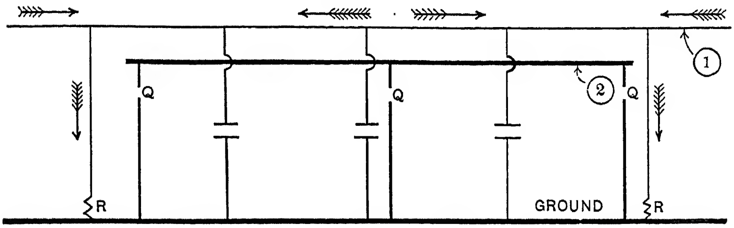


FIG. 24.—Diagram of overhead grounded wire on line

on the wire marked 1. Three condensers represent the distributed capacity of this wire. In the circuit of the transmission wire, marked 2, there are three gaps marked Q which represent the gaps at the insulators. With a given discharge of potential on the overhead grounded wire, the question is, what potential will be induced on the insulators?

Fig. 25 shows diagrammatically an equivalent circuit in the laboratory. It consists essentially of a loop within a loop.

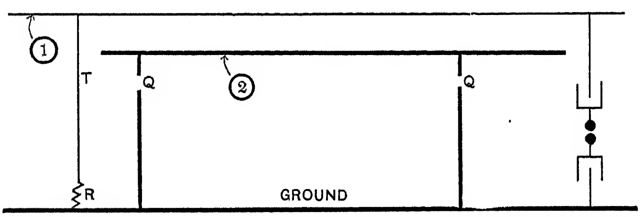


FIG. 25.—Laboratory connection in imitation of grounded wire

The leyden jars at the right were charged by a static machine and suddenly discharged. The following values are given for two concentric loops having a total length of parallel wire of approximately 200 ft. (60.96 m.). With an impressed potential at the jars represented by a gap of 2.55 inches (6.47 cm.) the induced potential on the line loop was 2.04 inches (5.18 cm.). The first test was made with a distance between loops of one

foot (30.4 cm.) and the second test with a distance of two feet (60.9 cm.). They both showed the same equivalent-needle-gap of 2.04 inches (5.18 cm.). That the greater distance should give the same induced potential was due perhaps to an accidental condition of partial resonance. The potential on the line was 80 per cent of the potential of the ground wire. This suffices for the present to emphasize the value of frequent grounding of the overhead wire. There is more work to be done before definite conclusion can be reached.

Protection by High Potential and Chance. Aside from the overhead grounded wire the natural conditions of growth to the use of higher voltages has led to a great improvement in two ways, *viz.*, chance and corona.

By the law of chance, potentials of lightning on a line have all values from a mere nothing to a direct bolt. If the line is insulated to withstand 25 kilovolts all lightning within that range is harmless to the line, but there will be, in general, numerous impulses of higher potential. If the line is insulated to withstand 200 kilovolts then there is added to the sum of the previously harmless impulses all those lying between 25 kilovolts and 200 kilovolts and the number above 200 kilovolts is comparatively few. Following up this reasoning and assuming the truth, in general, of the statement previously made that the lightning must either strike the line or else strike some distance from it, there must be a certain degree of insulation for the line which withstands the greatest induced stroke and is, therefore, affected only by direct strokes. Thus it would seem that the natural conditions of growth would reduce the problem of protection of trunk lines to the protection against side strokes and direct bolts. Perhaps 100 kilovolt lines are insulated to this critical value.

This relative degree of exemption from lightning as the line potentials are increased would make itself glaringly evident were it not for another law entering. An increase in potential accompanies naturally an increase in the length of line, and the increase in length increases directly the exposure to lightning.

Protection by Corona. The second way the higher voltages give a greater degree of immunity is through the loss of electrical energy in corona. In the use of high potentials, the critical potential of brush discharge falls naturally only slightly above the value of impressed potential. In fact in some recent propositions it has been necessary to increase the diameter of the line

wire to keep the brush potential above the impressed potential. When this condition exists then all superimposed potentials above the corona potential cause a self-destructive loss of the electrical energy in such a surge. This electrical energy is transformed into chemical energy—ozone is formed. The formation of chemical energy in ozone is not a reversible process. The suppression of the surge is complete and effective. The use of the overhead grounded wire gives a great degree of uniformity of corona discharge along the power wires. The grounded wire, by its proximity, thus relieves greatly the concentration of corona around an insulator. Without the overhead grounded wire, the relatively short air distance to ground at the insulator would give a higher potential gradient there than at any other point between insulating supports. The corona discharge would be strongest at the insulator and furthermore the insulators would be called upon to discharge the entire quantity of electricity between insulators. Heavy brush discharge easily changes into spark discharge, therefore, the insulator is more liable to failure without the overhead grounded wire.

If the formation of brush discharge has no time lag after the application of potential, then the rapid collection of static toward the bolt-point at the instant of cloud discharge, will lose its vicious electromagnetic inertia by discharging at every inch along the line. At the time of writing no specific measurements have been made on this subject of lag of brush discharge by the writer. Some information may be gleaned from the following paragraph.

It has been stated that surges of high potential can not cross the Rocky Mountains on the lines of the Central Colorado Power Company. The high part of the line is at such an altitude that the corona voltage is very little above the impressed voltage of the power. Consequently it appears that the surges at this point are lost in ozone.

On trunk lines it is possible to choose the diameter of the line wire and potential such as to suppress all induced potentials from cloud lightning and all internal surges between lines. This leaves still the problems of caring for a lightning stroke near a station, and a direct stroke on the line.

On the Design of Insulators. In the exemption from interruption the design of the insulator must play an important part, especially is this true if it is expected to get the beneficial action in full of the insulator protector described hereinbefore. The test for insulators has always been a gradual applied potential.

It is desirable to have the insulator flash around the petticoats rather than puncture. Testing out the separate petticoats and obtaining a flash-over at the limiting potential does not insure that, when assembled, the insulator will spill-over rather than puncture. Furthermore, a design which may spill-over on gradually applied potentials may puncture on suddenly applied potential. Investigation of the laws of flash-over have been made.

Line Construction and Design from a Protective Standpoint. Most of the elements of design are determined by mechanical requirements and cost of materials with reference to final economy. A discussion of either of these factors is beyond the scope of this paper. In any engineering problem there are always conflicting conditions to be met and the result is a compromise between these factors. In the following paragraphs an endeavor is made to show the elements entering into the problem of protection against lightning. One may choose wood or iron according to the voltage, cost of materials, kind of service, and locality. What is good practice in California may be poor practice in Brazil. What is good practice in the East may be poor practice in California.

In the different forms of construction the elements entering to affect the protective qualities against lightning are:

1. Wooden poles.
2. Wooden pole with vertical wire or metal tower.
3. Lightning rod extending above the pole or tower.
4. Wooden cross arm.
5. Wooden pin.
6. Wooden cross arm with metal pin.
7. Metal cross arm with wooden pin.
8. Grounded metal pin.
9. One overhead grounded wire.
10. Two overhead grounded wires.
11. Location of overhead grounded wires.

1. Wooden poles. From the meagre information of definite character that observation has given and from the theory, the statement is warranted that wooden pole lines are a little less liable to be struck than metal towers. When struck, however, the damage is frequently sufficient to necessitate renewals of poles. On trolley lines the wooden pole acts as an additional insulator against dynamic potential and is a valuable addition to lightning protection.

2. A wooden pole with a wire run vertically up its side is an equivalent, from a protective standpoint, of a metal tower with wooden crossarms. The presence of the vertical wire prevents damage to poles by direct stroke.

3. A lightning rod extending above a pole or tower gives, theoretically, a degree of immunity from the effects of direct stroke. No one has been able to observe whether the degree of protection warrants the expense. Assuming that a tower is struck it seems rather short-sighted to spend a considerable amount of money in overhead grounded wire and not add just a little more in an endeavor to keep the intense flame of the lightning stroke above and far enough away from the line to prevent its blowing between phases and causing a short circuit. If the insulation from each phase to ground is not sufficient to hold back the induced lightning when a tower is struck then the lightning rod is a useless expense. If the insulator is the smallest one designed for the specific voltage of the line and is set on a grounded iron pin, experience teaches quite definitely that the insulator would spill-over. Strokes 100 ft. (30 m.) from the line have caused such failures. However, with better insulation and with the possibilities of getting a certain number of light strokes or side strokes it is warrantable, it seems, to add the lightning rod in some cases.

4. Wooden crossarms, when they can be used, add enormously to the insulation of an insulator against lightning. Elsewhere the writer has given tests to show that a crossarm even when wet gives good lightning protection. Its use on high potentials where it is subject to burning off, if a failure of an insulator takes place, is justifiable only if by its use the number of interruptions become practically nothing. It is usually better practise to ground the pin and interrupt the power for an instant more frequently, than to use the wood, and undertake the great expense and loss of time in locating and repairing a less frequent fault in the line. The advent of the arcing ground suppressor also throws the argument strongly in favor of the grounded pin. In dry climates and with medium voltages, a line wire may be carried for days in contact with a wooden crossarm and not burn it off.

5. Wooden pin. On account of lack of strength the wooden pin has its limitations. On high voltages it is frequently digested by the static from the line. The wooden pin, has the same value as the wooden crossarm in giving greater spacing between metal parts and thereby cutting down the potential gradient. It increases the dielectric strength of an insulator.

6. Wooden cross-arms with metal pins. In this case it seems that the use of a metal pin instead of a wooden pin is permissible even from a protective standpoint. The metal pin has only its isolated capacity to draw a discharge from the line. The charging current to the pin can be obtained from a harmless corona streamer and there seems to be no appreciable danger of these streamers starting a grounding arc.

7. Metal crossarm with wooden pin. This is a combination not often found. Where the smallest possible insulator is used the wooden pin, where possible, will be of considerable value in increasing the insulation.

8. Grounded metal pin. This is the usual condition on high-tension lines dictated by mechanical requirements. As already indicated in a negative way in the discussion of wooden supports, the grounded metal pin requires the use of an insulator of larger dimension to give the same dielectric strength to ground as the normal insulator with a wooden pin. When the relative cost of the insulator to the rest of the line construction is taken into account, a large insulator, giving a large factor of safety, is justified. Where continuity of service is of great value the extra sized insulator is a good investment. Where economy is necessary it is usually better practice to put the investment in the insulation rather than in the overhead grounded wire.

9, 10 and 11. Overhead grounded wire. While engineers are generally agreed that overhead grounded wires give a considerable degree of protection—sufficient to justify the expense of their installation—there is almost nothing of definite character that has been given. Calculations on the screening effect with one grounded wire well above the line wires show a reduction in induced electrostatic potential of about 50 per cent. Laboratory tests give values of the same order. Two overhead grounded wires are better than one—the extra protection given is unknown. So far as induced charges are concerned it is possible to arrange tests which will give fairly definite values. It will probably be done some day. The conditions of protection against direct strokes are not amenable to experimentation and must be left to observation.

Conditions Without the Arcing Ground Suppressor

The practice followed by operators of transmission lines has varied considerably. The following classification is made:

1. The accidental arc to ground may be extinguished by the wind or other favorable condition.

2. The power may be discontinued to clear the fault.

3. The accidental arc to ground may be allowed to play until (*a*) It breaks the petticoats off the insulator, or (*b*) until the surges damage some apparatus or other insulator and cause a short-circuit, or (*c*) until it burns off the power wire.

1. *An Arc to Ground Extinguishing Itself.* Dr. Steinmetz has given some equations of the relation between current and arc length. These equations relate to conditions approaching unity power factor or lagging currents. There are no equations for arc lengths with the currents leading the e.m.f.

Since the current from a phase to ground supplies the quantity of electricity for the unbalanced electrostatic condition it is leading the e.m.f. to ground and produces, therefore, an unstable arc. During tests of a 20-mile (32 km.) 33-kilovolt transmission line, unloaded, with an average current to ground of 2.5 amperes, it was difficult to maintain an arc from wire to pin on an insulator designed for 45,000 volts, even when there was no wind blowing. To carry on the tests it was necessary to shield the arc from the wind and shorten it down to insure its continuance. This is a point in the design of a system that is well worth considering.

During the past lightning season there have been several cases of arcing grounds on the lines of the Southern Power Company that have cleared themselves. In the tests on the Schenectady Power Company's lines a small gap to ground was made between electrodes that sprung apart as soon as the arc burned off a string. When these electrodes were pulled away suddenly to a distance of four or five inches the arc to ground was frequently extinguished. The wave shapes of current in the arc vary widely depending on accidental shapes of the arc, its position relative to the vertical, the magnification of harmonics, etc. This matter is treated elsewhere. One of the important factors tending to extinguish the arc is the weakening or cooling of the arc by any means during the wave when the current is decreasing toward zero. This factor is especially important at the initial instant when the arc is struck. If the spark takes place during the period of decrease of potential there is a probability that insufficient metallic vapor will be formed to carry the conductivity over the period of zero current, which period is lengthened by the presence of electrostatic capacity. This condition together with the aid of a favorable wind perpendicular to the line cannot be depended upon except in rare cases.

2. *Discontinuance of the Power to Interrupt the Arcing Ground.* Since the dangerous nature of an arcing ground has become so generally appreciated, it has become the practice on many systems to open the main switch and shut off the power for a minute in order to rid the line of this electrical octopus. It is a heroic method but lacking other means, it is nearly always advisable.

3. *When an Arcing Ground is Allowed to Play.*

a. It cracks off the petticoats of the insulator. This cracking is due to unequal heating of the porcelain. In order to determine the characteristics of this action several samples of insulators were tried with different values of current. Some of the con-

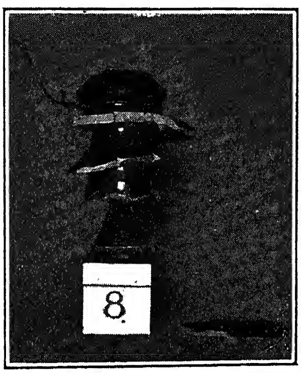


FIG. 26.—Test 8

Picture of insulator after four-ampere arc had played over it for 10 minutes
Dimensions of Insulator. Total height 6 in., (15.24 cm.) diameter of head 6¾ in. (17.2 cm.) diameter of middle shell 5 in. (12.7 cm.) diameter of bottom shell 3⅝ in. (7.77 cm.)

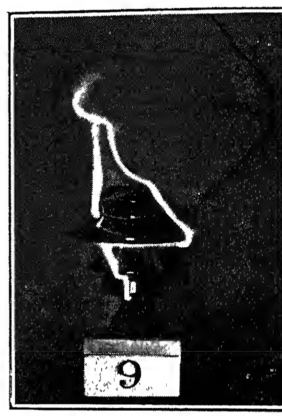


FIG. 27.—Test 9

Same type insulator as in test 8. Four ampere arc played for about one second—instantaneous photograph—insulator uninjured.
The arc does not rise under the two lower petticoats but it can be seen lying against the under surface of the upper petticoat to where it rises around the edge at the right and makes a high loop above the insulator back to the tie wire.

ditions of arc are shown in the accompanying photographs. The following summary covers most of the observations:

The arc is usually shifting from one place to another on the petticoats due probably both to local air currents and to the electromagnetic forces. As a four-ampere arc licks around the edge of a petticoat, little slivers of porcelain are thrown off successively with a snappy noise. It requires several minutes to wear away a petticoat this way. Sometimes the arc will rise under a petticoat and run around part way underneath, hugging the porcelain, before it rises around the edge. This is especially true in the case of the flatter upper petticoat. The arc of four

amperes must remain a considerable fraction of a minute in one place to split off a large piece of the petticoat.

Several illustrations are shown, Figs. 26 to 32 inclusive, with explanations which illustrate the foregoing summary. The circuits were inductive with a lagging current from an arc light transformer. This gives the arc a stable condition which is not present when the insulator is in normal operation on the line. The test gives a more severe condition of heating of the porcelain than would obtain in practical use of the insulator.

FIG. 28.—Test 11

Same type insulator as test 8—four-ampere arc played for about one second and then blew out—time exposure of entire phenomenon—insulator uninjured. The dissipated metallic vapor in the loop over the insulator, which caused the extinguishment of the arc is plainly visible in the photograph.

FIG. 29.—Test 14

Same type insulator as in test 8—four-ampere arc on for about 1½ minutes—time exposure of entire phenomenon—the insulator was considerably broken, especially the middle shell, one side of which was completely broken away. The porcelain was also heated red hot in spots.

The large flame in this photograph is not due to a large arc but to the movement during the 1½ minute of the same arc as in the previous tests. The maximum length of the arc was about two feet (60 cm.)

It will be shown later in tests on burning of line wires that large currents become safer to the insulators than certain smaller values due to the fact that the electromagnetic forces tend to throw the arc out into a long loop away from the porcelain.

b. The surges damage some apparatus or other insulator and thus cause a short circuit.

The *nature of the surges* produced by an arcing ground are not very well understood. Arcing grounds on some systems have been allowed with impunity to play ten hours and not produce any

noticeable damage. On the same circuit an arcing ground for as many seconds has produced short-circuits in the heart of transformer windings and caused spill-overs on transformer bushings. Although exact values of capacity and inductance to cause trouble are not known, there are several generalities which can, from experience, be stated positively. Every piece of apparatus has its own natural frequency—every coil its own, and different parts of a system each has its own natural frequency.

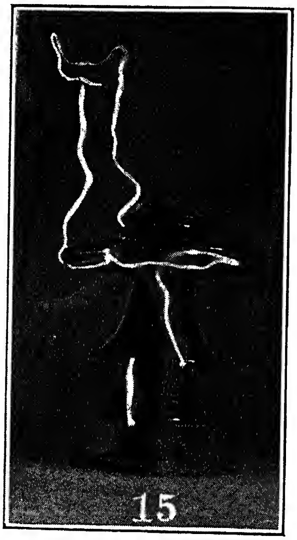


FIG. 30.—Test 15

Total height of insulator 14¼ in. (35.8 cm.) diameter of head 14 in. (35.5 cm.) diameter of middle shell 9½ in. (23.13 cm.) diameter of bottom shell 7⅛ in. (17.9 cm.). 2½-ampere arc played about two seconds—instantaneous exposure—the insulator was uninjured.

The arc follows the surface of the porcelain under every petticoat. From the middle petticoat it rises vertically to the upper petticoat, turns to the right, passes back, then to the left to the opposite outer edge.

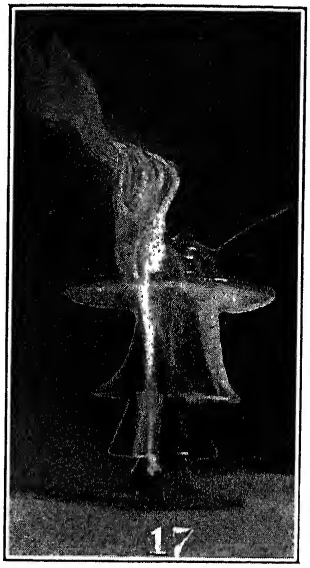


FIG. 31.—Test 17

Same type insulator as in test 15—2½-ampere arc played about four seconds and then blew out—time exposure of entire phenomenon—the insulator was uninjured.

The movement of the arc is shown by the hazy streaks. The denser parts indicate a greater or less halt in the movement.

If the frequency derived from the arcing ground corresponds to the natural frequency of some local circuit, resonance will result and unless the energy of resonance is absorbed by the natural conditions of load or by a special surge protector, a high localized potential will result. A considerable amount of data has been collected on specific conditions but the amount and nature of these tests and theories carries the matter outside the scope of this paper. Some generalizations regarding the

frequencies set up by an arcing ground may, however, be added. In any circuit where electrostatic capacity predominates to give a leading current, the arc will tend to be extinguished and relighted at the natural frequency—in other words, the arc magnifies every slight change in the circuit. Harmonics that are invisible in the e.m.f. wave often become in the arc current more prominent than the fundamental wave of the generator. The magnification of the higher frequencies depends greatly on the instability of the arc. The instability of the arc, in turn, depends on the relative values of arc length and arc current, also on the local conditions of cooling, and rectification effects of the metal vapor.

c. The Arc to Ground Burns Off the Line Wire. In the early work on the arcing ground suppressor, experiments were made to determine if the line wires could be burned off before the protector could operate. It was immediately evident that the burning in two of a line wire took so long that it would not be a factor in the design of the protector. An anomalous condition was encountered, however, which is of importance. Medium large currents will not burn off a wire where less current will.

FIG. 32.—Test 18

Same type insulator as test 15—2½-ampere arc played for about eight seconds and then blew out—time exposure of entire phenomenon—the insulator was uninjured.

In this case, although the exposure is twice as long as in the previous test, less trace of the arc is visible. This is explained by the fact that the arc was more constantly on the move.

Specifically, first, there is a certain limit of current which can be carried without overheating the wire at the crater of the arc. Second, a little greater current will soften the copper and the wire will separate. Third, a still greater current introduces electromagnetic forces which are sufficient to drag the arc out along the wire. This movement of the arc carries the arc-crater to new positions on the wire before the copper reaches a dangerous temperature. Once the arc is lengthened it sets up air currents which coöperate with the electromagnetic forces to keep the arc crater moving in and out along the wire. It is only when some accidental condition occurs which holds the crater in a spot for considerable time that the wire will fail.

These accidental conditions rarely occur. Fourth, when the arc current becomes very large the wire is again in danger of melting due to the fact that the energy loss at the crater is so great that if the crater tarries a moment in its movement the damage is done.

Experiments on Burning Off of Line Wires. Same numerical values are given below. The source of power was alternating current at 2,300 volts. The copper wires were stretched horizontally under two degrees of mechanical tension. Perpendicularly underneath each wire an iron insulator-pin was placed, leaving a gap of one-half inch. The arc was started by means of a fuse.

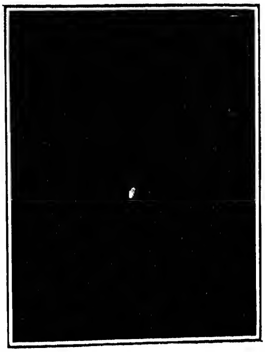


FIG. 33

Arc of 10 amperes on the line wire. The arc is about 2 in. (5.08 cm.) total height. The line wire is shown by the short central horizontal line. The wire burned off in 2.5 minutes.

FIG. 34

This arc was also at 30 amperes. It shows at the instant of exposure, a vertical and horizontal loop. Later the arc rose to nearly three feet before it broke.

A No. 6 B. & S. wire carried three amperes for 20 minutes without damage to itself. The wire became red hot, but the 20 lb. (9 kg.) of tension was not sufficient to break the wire.

Under the same conditions a current of six amperes caused the wire to separate in 2.3 minutes.

Next, a No. 4 B. & S. wire was used under a tension of 180 lb. (81.6 kg.)

It carried six amperes two minutes without damage. The wire around the crater was heated to a dull red; 8.4 amperes were then applied for two minutes without damage; 12.2 amperes were then applied for 0.7 minute without damage.

Twelve amperes being the limit of the series choke coils in use, a water rheostat was substituted and the current was in-

creased to 30 amperes with the idea of getting quicker burning. This did not occur. The arc left the shortest distance between the wire and pin. One crater traveled out along the wire and the other traveled vertically down the pin to its base. The result of this was an extinguishment of the arc in about one-quarter minute each time the potential was applied. The wire did not reach even red heat on account of the constant shifting of the crater.

Being impossible with the available potential to burn off the wire with 30 amperes, the current was reduced to 15 amperes and the wire separated at a point about one inch (2.5 cm.) to

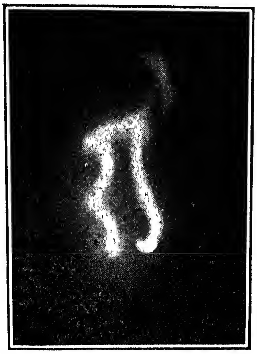


FIG. 35

This arc was also at 30 amperes initially. It was taken at a time when a long loop had just short circuited itself at about half way up its length. The upper part which was short circuited shows less metal vapor. The height was about three feet (91 cm.).

FIG. 36

The current in this arc was 15 amperes A time exposure was made. There is little movement of the craters of the arc. The arc flame rises to a height of over two feet (5.08 cm.).

the right of the point vertically over the pin in just one minute. The electromagnetic forces moved the arc out this far, but the resisting force exerted by the crater prevented any further movement.

Subsequently, further tests were made and photographs were taken of the arcs. These are shown in Figs. 37 to 40 inclusive.

CONCLUSION

This paper has been written during hours away from regular duties, and several parts of the original outline have had to be omitted on account of lack of time. A specific problem and its solution have been in the foreground, but it is impossible to separate it from some of the other problems, as they naturally

overlap. Some of these subjects treated will be expanded later when the remaining problems of protection are taken up. There are numerous minor problems, but the main problems which are to be solved before absolute continuity of service can be attained are: Protection against direct strokes of lightning, the suppression of short circuits, the suppression of internal surges, and the prevention of malicious or willful interference. More or less satisfactory solutions of all but the last mentioned problem are in sight. Will the demand for great continuity of service warrant the expense involved in getting such service? A collection of a considerable amount of data, shows conclusively, on analysis, that the greatest number of interruptions in lightning infested localities is due directly and indirectly to the single arcing ground around an insulator or in cable systems to a single puncture from one phase to the cable sheath. The arcing ground suppressor, backed up by aluminum arresters, will prevent interruption of service and damage to apparatus in the majority of these cases. This improvement should in general bring the service above the existing standards or requirements. It may be possible to meet the higher demands in the future as they grow.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

(*Subject to final revision for the Transactions.*)

TESTS OF ARCING GROUND SUPPRESSOR ON THE 40,000-VOLT SYSTEM OF THE SOUTHERN POWER COMPANY

BY C. I. BURKHOLDER AND R. H. MARVIN

The Southern Power Company experiences every year during the lightning season frequent disturbances and interruptions due to the lightning starting an arc over the insulator to the pin, this arc often breaking the insulators, or sometimes even burning off the line. With the object of extinguishing this arc before it has time to do any damage, an automatic insulator protector has been installed on the 44,000-volt system at the Catawba power house.

The power stations, principal substations and transmission lines of the 44,000-volt system are shown on the map, Fig. 1. This system is three-phase, 60-cycle, non-grounded. There is also a 10,000-volt system, and an extensive 100,000-volt system, not shown here.

The four power stations at present in operation are: Catawba, Great Falls and Rocky Creek on the Catawba River; and 99 Islands on the Broad River. Their rated capacities are: Catawba, 6600 kw.; Great Falls, 24,000 kw.; Rocky Creek, 24,000 kw.; 99 Islands, 18,000 kw.

Two of the lines between Great Falls and Catawba, and the two lines from Catawba to Gastonia are run on steel towers. All the other lines are on wooden poles. All insulators are three-part and are rated at 60,000 volts. The lines are partly copper and partly aluminum. The spacing of the wires is 6 ft. (1.5 m.) triangular.

The insulator protector was installed at Catawba, as this

location was convenient, and for some reasons the best. This device consists of three single-pole switches connected between the lines and ground, and controlled by a relay. If any phase becomes grounded, as for example, by an arc over an insulator, the relay causes the switch connected to that phase to close. The phase being grounded through the switch, the arc is short circuited and extinguished. This apparatus was designed by

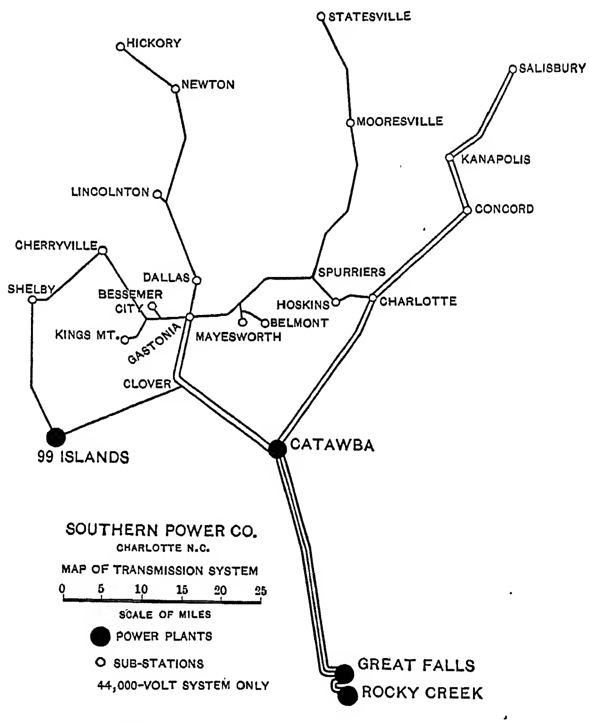


FIG. 1.—Map of 44,000 volt system of Southern Power Company

Professor Creighton; its theory and construction are fully treated in his paper, so that no further description is necessary here. The switches are connected to the bus at the Catawba station. The bus is in two sections; one connected to the Charlotte lines, the other connected to the Gastonia lines. The two sections are usually connected together by a bus junction switch. The grounding switches are on the bus connected to the Gastonia lines.

Description of Tests

Object of Tests. The features in the operation of this device, which it was desired to determine were as follows:

1. The time required for the operation of the relay and the various operations of the switch.
2. The total time an arc would exist over an insulator.
3. The time required to extinguish the arc after the switch had closed.
4. The current to ground through the arc over an insulator.
5. The current to ground through the grounding switch.
6. Whether the arc could be extinguished soon enough to prevent breaking or injuring the insulator.

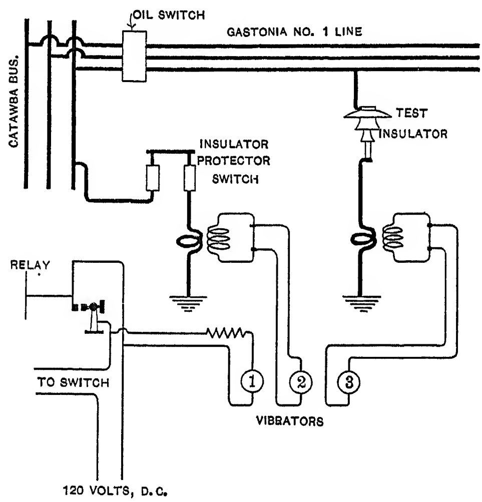


FIG. 2.—Connections of oscillograph

Method of Test. A regular line insulator was suspended by its head from one leg of the No. 1 line going to Gastonia. Its pin was connected to ground through a current transformer. A five-mil resistance wire was tied around the insulator from the head to the pin. On closing the oil switch which connected this line to the bus, the fine wire would start an arc around the insulator, which would hold until extinguished by the grounding switch. The insulator was the same type as is used on most of the lines. The principal dimensions of this insulator are: diameter of headpiece, 12 in. (30 cm.); diameter of intermediate shell, 10 in. (25.5 cm.); diameter of bottom shell, 7 in. (17.8 cm.);

height over all 13¼ in. (43.5 cm.). The pin of the insulator was thoroughly grounded by connecting it to the common ground at the station used for all lightning arresters and apparatus.

The connections of the test insulator, grounding switch and oscillograph are shown in Fig. 2.

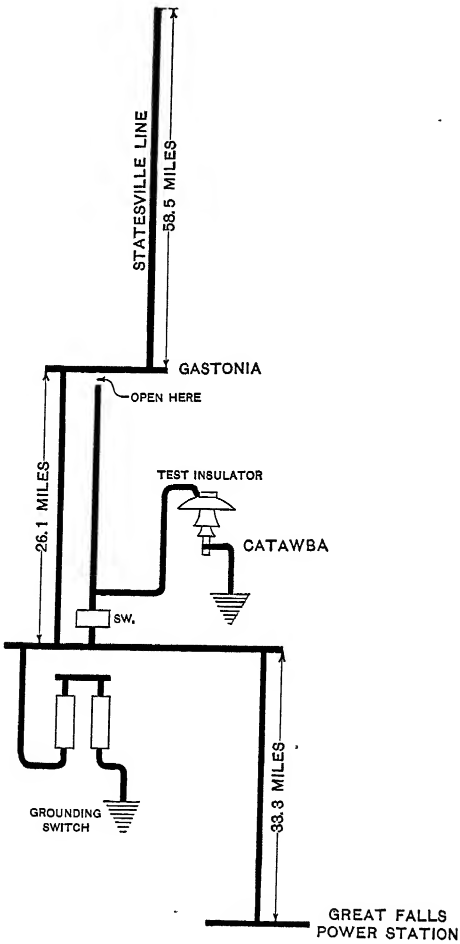


FIG. 3.—Connection diagram, tests 1 and 2

Oscillograph Connections. Currents and times were recorded by an oscillograph connected as follows, Fig. 2:

Vibrator No. 1 (the top record) was connected across the contacts on the relay, which would close when a ground occurred.

The closing of the relay contacts would then short circuit the vibrator and reduce its deflection to zero.

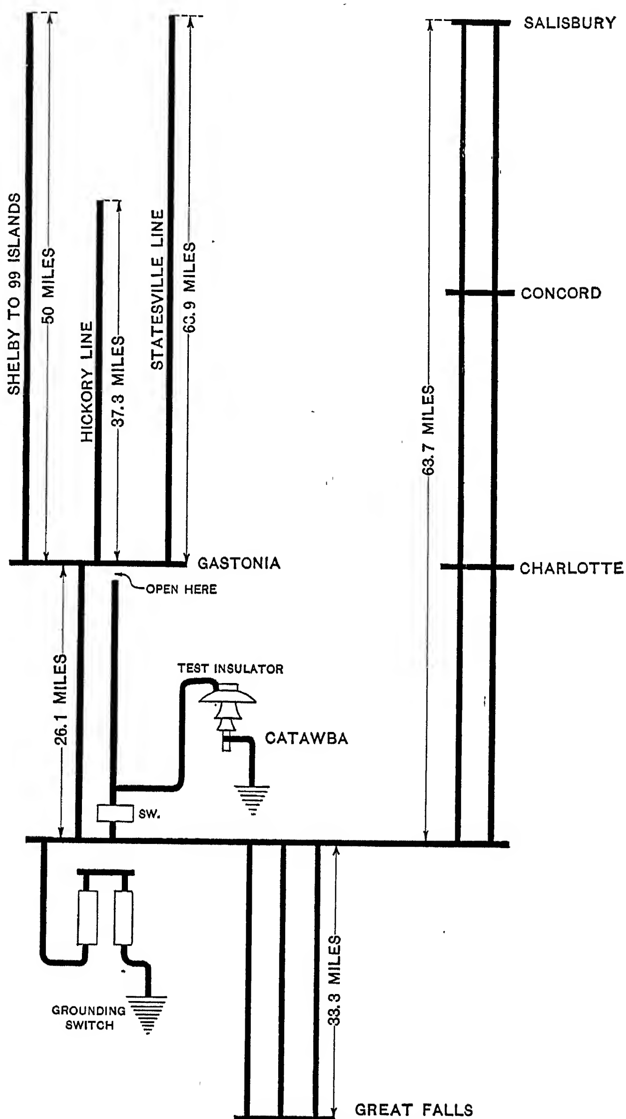


FIG. 4.—Connection diagram, tests 4 and 5

Vibrator No. 2 (the middle record) was connected to a current transformer in the grounding switch circuit.

Vibrator No. 3 (the bottom record) was connected to the current transformer in the ground circuit of the test insulator.

Source of Power. In all tests power was supplied from Great Falls by two, 3000-kw. generators.

Test No. 1. Fig. 3 shows the connections and lengths of the lines. The total length of the power lines was 144 miles (231.7 km.). The arc was extinguished at once and without disturbance to the system. Fig. 5 shows the arc over the insulator. A summary of the principal points shown by the oscillogram is given in Table No. 1.

Test No. 2. This was a duplicate of Test No. 1 and showed the same results. Fig. 6 shows the arc over the insulator. Fig. 9 is the oscillogram.

Tests Nos. 3 *A*, *B*, *C*, *D*. These tests were made to determine the action of the relay and switches when the ground was due to an arc over such a short distance that the line voltage could re-establish it after being extinguished. For this the No. 00 copper wire which grounded the pin of the test insulator was bent up, so that its end came within about an inch of the No. 00 copper wire attached to the head. The voltage to ground could, of course, spark across this distance and start an arc. The connection of the lines was the same as in the two previous tests, Fig. 2. This test was tried four times, with the following results: The arc started and the grounding switch closed. This extinguished the arc, and the switch at once opened. But before the switch was fully open, the arc started a second time. This brought the second stroke lock-device into operation, and the switch closed a second time and stayed closed. This permanently put out the arc, but, of course, left the system grounded.

Test No. 4. Fig. 4 shows the connections and lengths of the lines. The total length of the lines was 428 miles (669 km.). This was the entire system, with the exception of one section, 17 miles (27 km.) long. The arc was rather heavy, but was at once extinguished, and without disturbance to the system. Fig. 7 shows the arc over the insulator. Fig. 10 is the oscillogram.

Test No. 5. This was a duplicate of Test No. 4, and gave the same results. Fig. 8 shows the arc over the insulator. In all these pictures of the arc, the exposure was 0.04 second, and therefore the arc is probably shown during several cycles.

Effect of Arc on Insulator. The same insulator was used in all tests. It was absolutely uninjured. There was not even any

chipping or cracking of the glaze, and no blemishes further than a little smoking.

It will be seen from the oscillograms that the time from the starting of the current in the switch to the extinguishing of

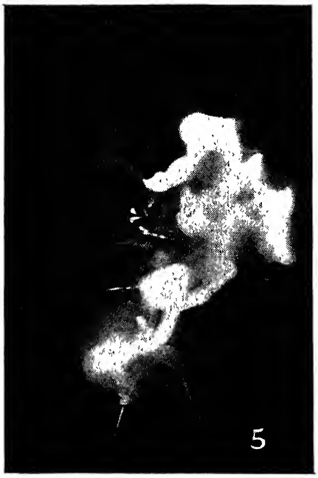


FIG. 5

FIG. 6

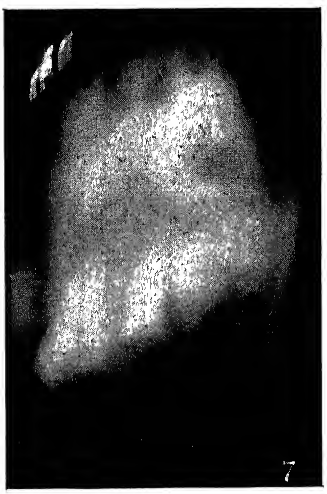


FIG. 7

FIG. 8

the arc is about two cycles. This is the time for the switch to move from the auxiliary contact to the main contact, during which time the oscillation damping resistance is in circuit.

TABLE NO. 1
ANALYSIS OF TESTS NUMBERS 1, 2, 4, 5

Test number.		1	2	4	5
Time for relay to close	Cycles.........	4.5	4.5	4.25	4.5
	Seconds.........	0.075	0.075	0.071	0.075
Time for switch to close	Cycles.........	24.5	22.5	24.0	21.5
	Seconds.........	0.408	0.374	0.401	0.358
Time arc is on	Cycles.........	29.0	27.0	28.25	26.0
	Seconds.........	0.483	0.449	0.472	0.433
Average current in arc, amps.	Maximum......	70.	76.	247.	247.
	Effective.......	50.	54.	175.	175.
Average current in switch, amps.	Maximum......	63.	76.	240.	240.
	Effective.......	45.	54.	170.	170.

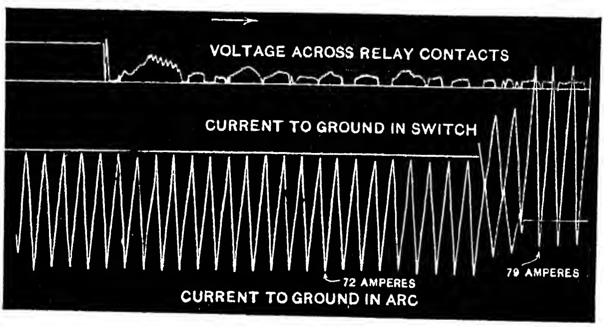


FIG. 9

The effective currents given in the table have been calculated from the maximum values on the assumption of a sine-wave form. Fig. 11 is a high-speed oscillogram from a later test

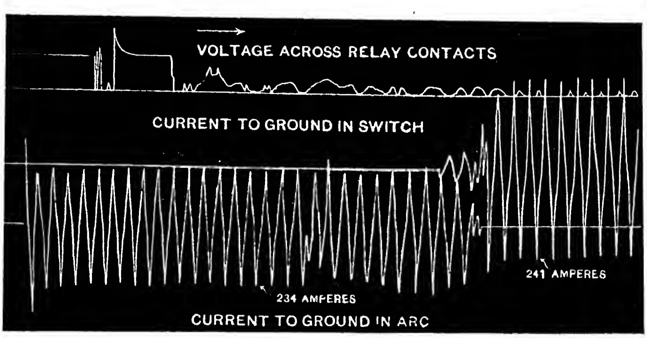


FIG. 10

which shows the wave shape of the current in the arc. This wave has a very pronounced third harmonic. An approximate

analysis, gave as its equation, taking unity as the maximum value of the fundamental.

$$I = 1.000 \sin (\theta + 2.5°) - 0.201 \sin (3\,\theta + 11.5°) - 0.048 \sin 5\,\theta$$

This wave is so much peaked that the ratio of the effective to the maximum value is much lower than for a sine wave. It was not possible to make sufficient tests to determine whether the wave distortion was the same in all cases, and therefore, no correction of the current values for the wave shape has been attempted. But it seems probable that the actual effective values are slightly lower than those given in the table.

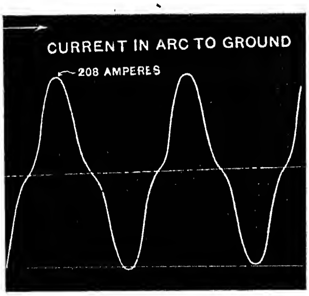


FIG. 11

Summary of Tests. An examination of these tests shows:

1. The current in both the arc and the grounding switch depends upon the extent of the lines on the system. This is to be expected, as these currents are flowing into a capacity, this capacity being proportional to the length of the lines.

2. The arc is extinguished in a time not exceeding one-half second from the time of starting.

3. The insulator being uninjured, shows that even the very heavy arcs produced when the entire system is on will not injure the insulator when extinguished in one-half second.

4. When the arc is extinguished in such a short time, there is no disturbance on the lines or interruption of service either from the arc, or the operation of the grounding switch.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

TESTS OF LOSSES ON HIGH TENSION LINES

BY G. FACCIOLI

It is generally admitted that corona losses constitute the most serious objection to the use of higher voltages in transmission lines. For this reason a number of physicists and engineers have devoted and are devoting their attention to the study of corona phenomena. Their investigations can be divided into two classes.

First: Investigations in laboratories, where conductors of limited length and apparatus of comparatively small size are experimented upon.

Second: Investigations on high-tension lines under operating conditions or on experimental lines.

Since the opportunities for investigations of the latter category are limited, it seems advisable that the results of such experiments—though they may be incomplete—be gradually collected, until sufficient data are secured to warrant the deduction of reliable conclusions.

As a contribution to such a collection, this paper gives the results of tests taken on the lines of the Central Colorado Power Company. An investigation was undertaken on this power system to study line oscillations and switching phenomena and this will form the subject of a future paper. However, while the main investigation was in process, some tests on line losses were performed which, owing to the peculiar topographical conditions of this system, will prove of practical interest.

Fig. 1 is a map of the system.

The main Power House is located at Shoshone.

The three conductors of the three phase line are situated on

a horizontal plane, with a distance of 124 in. (3.14 m.) between centers of adjacent conductors.

Each conductor between Shoshone and Denver consists of a hemp center, six-strand, copper cable, No. 0 B. & S. gauge, with the exception of a section between Leadville and Dillon where

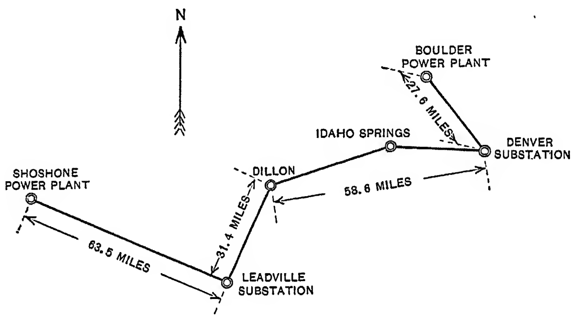


Fig. 1

the conductors are of smaller size. From Denver to Boulder three, six-strand copper cables, No. 1 B. & S. are used.

As shown in Fig. 1, the length of the transmission line from Shoshone to Denver is 153.5 miles (247 km.) of which 63.5 miles (102 km.) are from Shoshone to Leadville, 31.4 miles (50 km.)

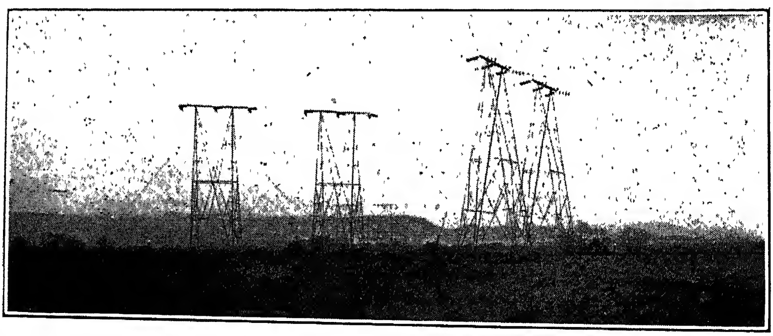


Fig. 2

from Leadville to Dillon and 58.6 miles (94 km.) from Dillon to Denver.

The distance between Boulder and Denver is 27.6 miles (44 km.)

Power is delivered to Denver from Shoshone and Boulder, but

at the time of the tests the Shoshone power house only was in operation. Fig. 2 shows the towers of the system. The insulators are all of the suspension type and have four insulating disks each.

The altitude and the climatic conditions of the country traversed by the transmission line are unusual. The line crosses the continental divide at three points, one between Shoshone and Leadville at an altitude of 12,000 ft. (3,657 m.), another between Leadville and Dillon at 12,500 ft. (3,810 m.), and the third between Dillon and Denver (Argentine Pass) at 13,700 ft. (4,175 m.). These exceptional conditions magnify the importance of the problem of line losses, as it is well known that the atmospheric losses increase with the altitude.

The 153.5 miles (247 km.) of line (from Shoshone to Denver)

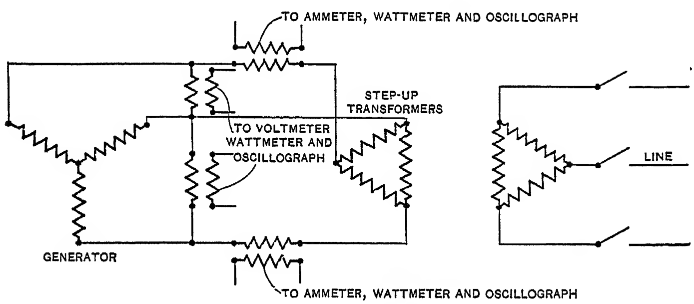


FIG. 3

were energized from Shoshone as shown in Fig. 3. The line was entirely unloaded, no apparatus being connected to it with the exception, of course, of the generating system at Shoshone.

This consisted of a 5,000-kw., 4000-volt, 60-cycle, three-phase alternator, connected to the low-tension side of three 3,333-kw. transformers, whose ratio of transformation was 4200 to 100,000 volts.

The generator windings were Y-connected, the three transformers being delta-connected on both primary and secondary sides.

Fig. 4 gives the kilowatt losses of this three-phase line(153.5 miles long) in function of the voltage between conductors at the power house.

The voltage was varied by regulating the excitation of the alternator and the measurements were taken on the low-tension

side of the step-up transformers as follows: First, the transformers alone were connected to the generator, and the transformer losses recorded at a certain voltage; Second, the line was connected to the high-tension terminals of the transformers and the loss measured at the same low-tension voltage.

The difference between the two readings gave the total line losses, *i.e.*, the sum of ohmic, corona and insulator losses. This simple method of measurement is subject to criticism, but it

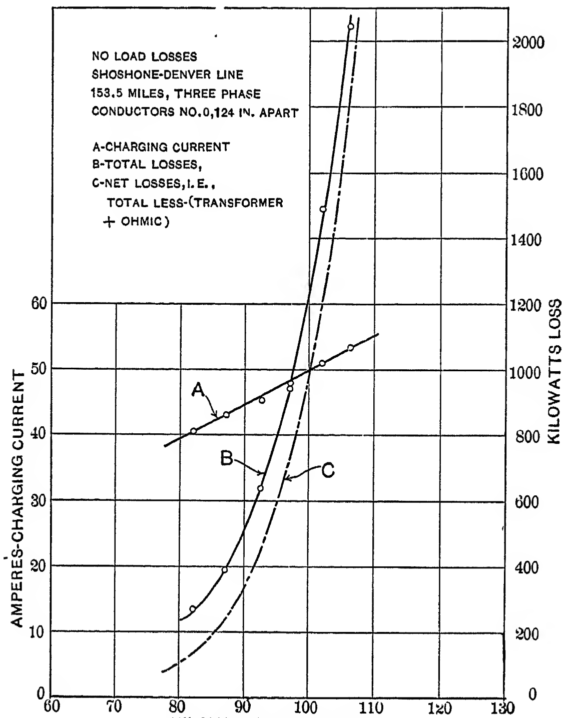


FIG. 4

was followed as the only one available, as there was neither time nor opportunity to procure special apparatus or to provide elaborate arrangements.

As Fig. 3 shows, the currents were measured through a series transformer. This introduces an error into the measurements of the kilowatts, which amounts to 1.5 per cent at 100 kilovolts. Oscillograms of the e.m.f's. and currents were taken, and practically sine waves were obtained in every case. The waves of the

generator e.m.f. were identical whether the transformers only were excited, or both the transformers and line were energized, and therefore the results may be considered accurate enough to substantiate the conclusions which follow and which are more qualitative than quantitative.

It must also be noted that since the low-tension side of the transformer was delta-connected, the triple frequency component of the exciting current was circulating in the delta and did not affect the ammeter readings and oscillograms of current.

Fig. 5 gives the e.m.f. and current energizing the Shoshone-Denver three-phase line. The record is taken at the generator end of the line at Shoshone according to the connections shown in Fig. 3. The voltage corresponds to 91.5 kilovolts between line conductors, and the current is 1080 amperes flowing in the generator windings.

In Fig. 4, curve *A* shows the charging current of the line and

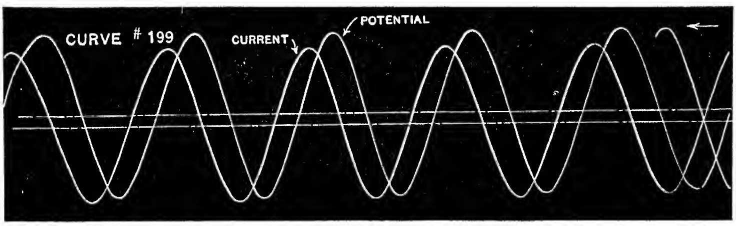


FIG. 5

curve *B* gives the total losses measured at different voltages, that is to say, the line losses plus the transformer losses. Curve *C* gives the corona and insulator losses, *i.e.*, the losses remaining after the ohmic and the transformer losses have been subtracted from the total measured losses.

The following table gives an idea of the relative importance of the transformer losses and line losses.

Kilovolts at Shoshone	Transformer losses	Corona and insulator losses
80	24	109
90	36	341
95	43	598
100	52	1003
105	64	1623

At 100 kilovolts, which is about the operating voltage of the system, the line losses under these conditions are 1000 kilowatts. Thus the operation of this system at 100 kilovolts would appear impracticable. However, when the system is loaded and in normal operation the line losses fall to small values, well within the limits of economical operation. The explanation of this phenomenon is obvious.

When the line is unloaded the voltage, which is 100 kilovolts

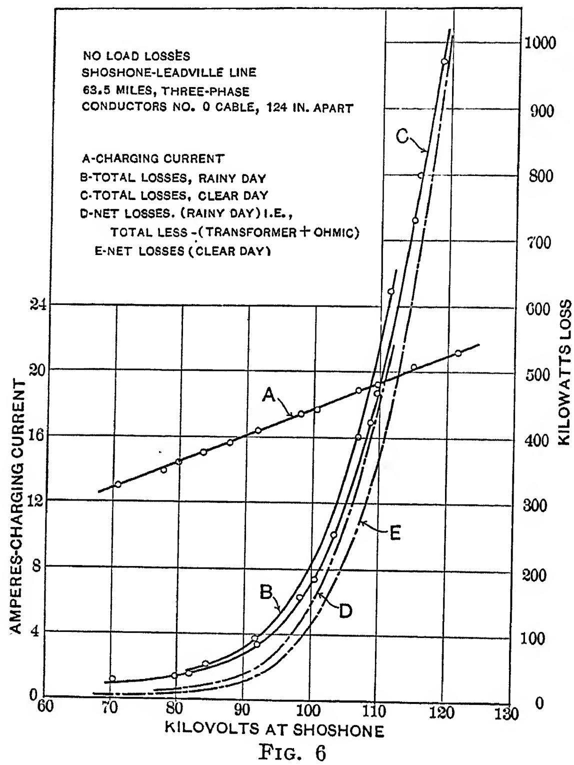


FIG. 6

at Shoshone, increases along the line, until at the far end of the line, at Denver, it is more than 10 per cent higher than at Shoshone.

The voltage at Denver could only be measured by connecting step-down transformers at Denver and measuring the potential on their low-tension side. Of course, the case of the open line is different as the exciting current of the step-down transformers, flowing through the line, modifies the conditions.

With two 2500-kw. transformers connected at Denver in open delta it was found that with 90 kilovolts at Shoshone the voltage at Denver was 100 kilovolts.

Hence the majority of the 1000 kw. measured when 100 kilovolts were held at Shoshone, were concentrated at the far end of the line, where the voltage was above 110 kilovolts.

As a proof of this the section of the line from Leadville to Denver was disconnected at Leadville and the three-phase losses of the section Shoshone-Leadville (63.5 miles, 102 km.) were measured, following the same method described above. Fig. 6 gives the results of these last measurements.

Curve *A* gives the charging current of the line.

Curve *B* the total losses (corona, ohmic, insulator and transformer losses) in rainy weather.

Curve *C* the total losses (corona, insulator, ohmic and transformer losses) in clear weather.

Curve *D* the corona and insulator losses deduced from curve *B*.

Curve *E* the corona and insulator losses deduced from curve *C*.

The following table deduced from curve *C* of Fig. 4 and curve *D* of Fig. 6 gives the losses of the line from Shoshone to Denver, the losses of the section from Shoshone to Leadville and the difference between the two values:

Kilovolts at Shoshone	Kilowatts Shoshone to Denver	Kilowatts Shoshone to Leadville	Difference
80	109	10.6	98.4
90	341	37.9	303.1
100	1003	152.	851

It follows that at 100 kilovolts held at Shoshone 63.5 miles (102 km.) of three-phase line give a loss of 150 kilowatts, but when 90 additional miles (27.4 km.) are connected at the end of this section, bringing the total length of line to 153.5 miles (247 km.), the losses become 1000 kw., *i.e.*, adding 90 miles (27.4 km.) of line introduces a loss of 850 kw.

The average atmospheric conditions for the tests of curve *B* Fig. 4 are

Barometric pressure......................23.8 in. (604.5 mm.)
Temperature dry thermometer.............51 deg. fahr.
Relative humidity.......................87 per cent

These measurements were taken at Shoshone and therefore they represent the atmospheric conditions at one point of the line only.

For curve B of Fig. 6 the atmospheric conditions were the same as before while for curve C Fig. 6 the conditions were

Barometric pressure	24 in. (609.5 mm.)
Temperature dry thermometer	55 deg. fahr.
Relative humidity	45.5 per cent

The difference between curve B and curve C is due to the fact that while curve B was taken in rainy weather the measurements of curve C were obtained in clear weather.

Although the Shoshone-Leadville tests were taken on a section of line 63.5 miles (102 km.) long, still the curves of Fig. 6 cannot be used to determine the critical voltage or the law which connects losses to kilovolts, because the voltage at the far end of the line is higher than the voltage at the power house and because of the different altitudes through which the transmission line runs. For this reason some experiments were conducted on the Denver-Boulder section of the system.

The distance between Denver and Boulder is 27.6 miles (44.4 km.) and the line runs at an average altitude of 5300 ft. (1615 m.) The conditions of the majority of the tests were as follows:

The main line from Shoshone to Denver was energized under normal conditions. The voltage at Denver was stepped down from 100,000 volts to 13,200 volts and power was delivered at this voltage to the 13,200-volt bus bars at Denver. The low-tension winding of a 2,500 kw., single-phase, step-up transformer was connected to these bus bars, and the high-tension winding energized two of the conductors of the three-phase line from Denver to Boulder. Different voltages were obtained by using different ratios of transformation or different combinations of step-down and step-up transformers. Fig. 7 is a sketch of the connections used.

The method of measurement was the same as the one employed at Shoshone, with the difference that the wattmeter was not used through a series transformer but its current coil was connected directly in the 13,200-volt circuit. This eliminates the error due to the phase displacement introduced by the current transformer. The potential coil of the wattmeter was, however, energized through a potential transformer.

Fig. 7 shows how the conductors of the Denver-Boulder line are transposed. In these tests two conductors only were energized, and the potential of the third conductor, measured by electrostatic voltmeter, was zero in every instance.

The measurements were taken for a period of two weeks

during which the barometric pressure varied from a minimum of 24.1 in. (612 mm.) to a maximum of 24.7 in. (627 mm.); the temperature varied from 49 deg. to 74 deg. fahr. and the relative humidity from 21 to 35 per cent with an average of 29 per cent. These values were measured at Denver. It was found that readings taken on different days were not affected by humidity, for which, therefore, no correction was made. Also no correction was made for the slight difference in barometric pressure and temperature.

The results regarding humidity obtained in Colorado corroborate the tests taken in Pittsfield, where an apparatus, consisting of a rod parallel to a plate, was tested for corona during

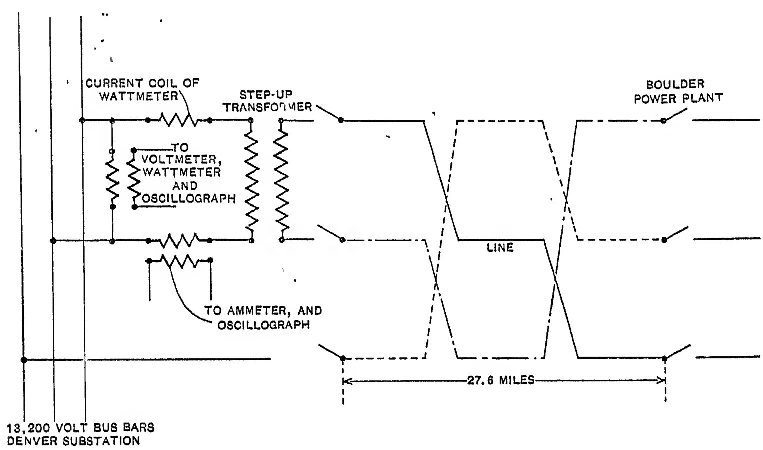


FIG. 7

the period of a month. The voltage at which luminous corona appeared remained constant although the vapor product varied from 0.36 to 1 and the relative humidity from 43.5 per cent to 78 per cent. The barometric pressure varied between 28.7 in. (729 mm.) and 29.2 in. (742 mm.).

The Pittsfield tests prove that vapor product has no influence on the visual critical voltage of corona and in the Colorado tests no influence of the vapor product on line losses could be detected. This last point, however, cannot be definitely settled without further investigation in different seasons of the year and under more widely varying climatic conditions.

Oscillograms of e.m.f. and current were taken at different voltages and it was found that the shape of the wave of the

e.m.f. remained constant throughout the tests. Fig. 8 is a representative oscillogram, and gives the voltage applied to the low-tension side of the transformer which energized the line, and the current flowing through the low-tension side of the transformer. This current was taken through a current transformer, and is the algebraic sum of the charging current of the single-phase line at 87 kilovolts and of the exciting current of the step-up transformer at the same voltage. The current is 31.53 amperes. The analysis of the current wave gives the following results:

Effective	value	of	fundamental		25.5	amperes
"	"	"	3rd harmonic		11.0	"
"	"	"	5th	"	6.14	"
"	"	"	7th	"	13.15	"
"	"	"	9th	"	0.93	"
"	"	"	11th	"	2.63	"

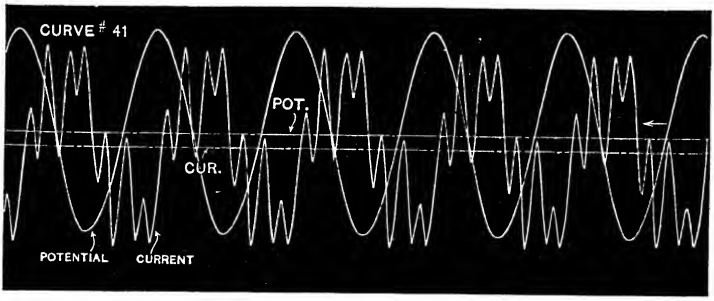


Fig. 8

The third harmonic is introduced by the magnetization of the transformer, and the fifth and the seventh are emphasized by line capacity.

The curve of Fig. 9 gives the losses of 27.6 miles (44.4 km.) of single phase line (see Fig. 7), the conductors being No. 1 B. & S. copper cable, 124 in. (3.14 m.) apart for two-thirds of the distance and 248 in. (6.28 m.) for the remainder of the distance. Transformer and ohmic losses were subtracted from the total readings and the ordinates of the curve are the corona losses of the two conductors plus insulator losses.

An attempt was made to separate insulator losses from corona losses but the insulator losses (which were measured in dry weather only) were so small that no definite measurement of their value could be obtained, and they are neglected in the following discussion.

The voltage at the Boulder end of the line was measured by connecting a step-down transformer at Boulder and reading the voltage on the low tension side of this transformer. The voltage at Boulder resulted 2 per cent higher than at Denver.

Since the power factor of the readings was very low it was considered advisable to raise this power factor by using an artificial load (a water box) in multiple with the low-tension winding of the step-up transformer which energized the line. The measurements were taken as follows:

The transformer only was connected to the system and read-

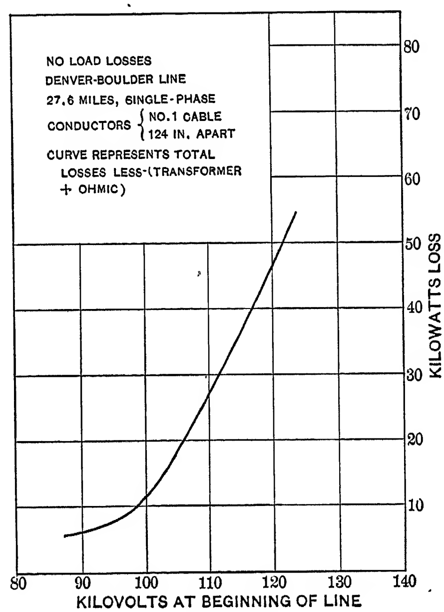


FIG. 9

ings taken, then the line was connected to the transformer and readings taken at the same voltages as before. The difference between the kilowatts in the two cases gives the total losses of the line. Additional measurements were made, first, with the transformer and auxiliary load; second, with the transformer, auxiliary load and line. The utmost care was taken to keep the auxiliary load constant during these two sets of measurements. The introduction of the auxiliary load proved unnecessary as the results obtained with and without the extra load were the same.

In order to find an equation representing the curve of losses the following method was adopted. The points of the curve were plotted on logarithmic paper, using the logarithms of the kilowatts in function of the logarithms of the kilovolts, and the logarithms of the kilowatts in function of the kilovolts. The results were not satisfactory. Then the curve was differentiated, in order to obtain a preliminary idea of its form.

In the following table the first column gives the value of the kilovolts (abscissæ) taken at a constant interval of 2.5 kilovolts; the second column gives the kilowatts (ordinates) corresponding to the kilovolts of column 1. Column 3 (Δ kilowatts) gives the difference between consecutive values of column 2 and therefore represents the differential of the kilowatts. If the values of column 3 are divided by 2.5 (Δ kilovolts) the quotients are the derivatives of the kilowatts with respect to the kilovolts. Column 4 gives the kilowatts corresponding to the values of kilovolts mid-way between the values given in column 1. Column 5 gives the ratios between the values of column 3 and the values of column 4.

I Kilovolts	II Kilowatts	III Δ kilowatts	IV	V $\frac{\Delta \text{ kilowatts}}{\text{Kilowatts}}$
122.5	52.4			
		5.4	49.7	0.1085
120	47			
		5.2	44.4	0.117
117.5	41.8			
		5.1	39.3	0.127
115.	36.9			
		4.8	34.45	0.139
112.5	32.1			
		4.6	29.8	0.15
110	27.5			
		4.4	25.3	0.174
107.5	23.1			
		4.3	21	0.204
105	18.8			
		3.8	16.8	0. 26
102.5	15.			
		3.3	13.2	0.25
100	11.7			
		2.2	10.6	0.208
97.5	9.5			
		1.5	8.7	0.175
95.	8			
		1.2	7.4	0.162
92.5	6.8			
		0.6	6.6	
90	6.2			
		0.6	5.9	
87.5	5.6			
		0.6	5.3	
85	5.			

In curve *A* Fig. 10 are plotted the values of column 3. At 107.5 kilovolts, the curve of the differentials changes sharply

its direction and form. Above 107.5 kilovolts curve A is a straight line, hence the law giving the kilowatts in function of the kilovolts (above 107.5 kilovolts) is represented by a quadratic equation. Below 107.5 kilovolts curve A is identical in form to the integral curve of Fig. 9, showing that the law giving the kilowatts in function of the kilovolts below 107.5 kilovolts is represented by an exponential equation.

Between 97.5 and 107.5 kilovolts, we may assume that the values of column 5 are constant and equal to the average value 0.222.

The exponential equation is of the general type kw. $= Ae^{B\,(\text{kv.}-C)}$ where e is the base of the Naperian logarithms,

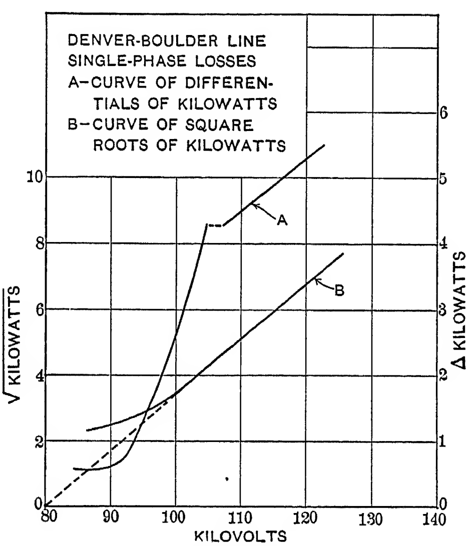


FIG. 10

A and B are constants and C is also constant and is the critical voltage at which the exponential law begins.

The above table shows that C is equal to 97.5 kilovolts.

B is the ratio between the values of the derivatives and the values of the ordinates of the integral curve and is equal to

$$\frac{0.222}{2.5} = 0.089.$$

A represents the losses at the critical voltage (97.5 kilovolts) *i.e.*, 9.5 kilowatts.

We conclude that between 97.5 and 107.5 kilovolts the ex-

ponential law which gives the kilowatt losses in function of the kilovolts is kw. $= 9.5e^{0.089\ (\text{kv.} - 97.5)}$. The following table gives the values of the losses calculated with the above equation and the values of the kilowatts deduced from the curve of Fig. 9.

Kilovolts	Calculated kilowatts	Tested kilowatts
110	28.8	27.5
107.5	23.1	23.1
105	18.5	18.8
102.5	14.8	15
100	11.84	11.7
97.5	9.5	9.5
95	7.61	8
90	4.89	6.2

As had been anticipated, the test points agree with the points given by the exponential law between 97.5 and 107.5 kilovolts.

This is shown again in Fig. 11 where curve A is the graphical representation of the exponential equation. It would not be unreasonable to admit that the law controlling the losses in function of the kilovolts changes sharply at a certain definite point, and the phenomenon may be explained by the hypothesis that the diameter of the conductors increases, due to corona, up to a certain limit, after which the diameter remains constant and the losses follow a different law.

However, it is impossible to draw conclusions of this nature from the study of one curve only and furthermore it is not advisable to rely upon results derived from the differential of a function, because a large variation in the slope of the curve may correspond to a small variation in the ordinates of the integral curve.

Now, curve A of Fig. 10 is a straight line above 107.5 kilovolts and from the constants of this straight line it is possible to derive the quadratic law which gives kilowatts in function of kilovolts. But on account of the uncertainty regarding derivatives of functions, as explained above, a different method was used. This method consists in plotting the square root of the kilowatts in function of the kilovolts. Curve B of Fig. 10 was thus obtained.

The upper part of this curve is a straight line down to a point corresponding to 97.5 kilovolts and it is remarkable that this is the same voltage at which the exponential law starts. The

quadratic law has the general form kilowatts = D (kilovolts $- E)^2$, in which E is the voltage at which the upper straight line of curve B, Fig. 10, cuts the axis of abscissæ, namely, 80 kilovolts. D is readily figured from any point of the loss curve and the equation becomes kilowatts = 0.0306 (kilovolts $-$ 80)^2. This equation is represented graphically in curve B of Fig. 11. The tested points check fairly well with the quadratic law above 97.5 kilovolts and the exponential law appears unnecessary.

These results show the necessity of a clear understanding as to the method of determining the so-called " critical voltage ".

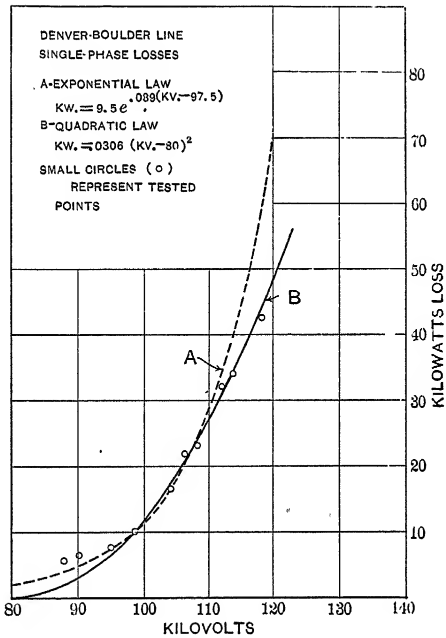


FIG. 11

In this case 97.5 kilovolts is a " critical voltage " because above this point the curve of losses follows a definite law different from the law followed below this point; 80 kilovolts is also a " critical voltage " as shown by the quadratic equation.

These voltages are different from the critical voltage which would be obtained by following Mershon's method, according to which no definite law is applied in determining the point at which the lower and upper limb of the curve meet. Following Mershon's method we should judge that the critical voltage in this case is 92.5 kilovolts.

It appears that 80 kilovolts is in this case the most definite voltage which can be called " critical " and if the results of other experiments will confirm this conclusion it is advisable to call " critical voltage " the voltage at which loss, as given by the quadratic equation, begins.

An attempt was made to find the critical voltage which should be expected in this case using the data published by Mershon in the TRANSACTIONS of the A. I. E. E., 1908. Fig. 39 of Mershon's paper shows the relation between the critical voltage and the distance between conductors, for different sizes of conductors.

The law generally accepted to give the critical voltage at which

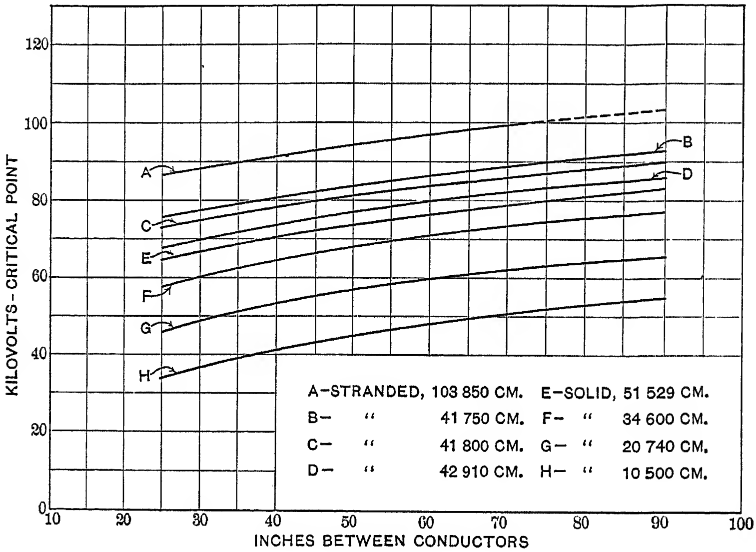


FIG. 12

corona appears in function of the diameter of the conductors and the distance between conductors is $V = M\, r \log \frac{D}{r}$, where M is a constant depending upon the barometric pressure and temperature, D is the distance between the centers of the conductors, r the radius of the conductor. A glance at the curves of Fig. 12 (which are a reproduction of the curves of Fig. 39 of Mershon's paper) shows that the above law does not hold in this case. In fact, the increase in critical voltage due to an increase in spacing of the conductors is constant, and therefore independent of the radius of the conductor.

For solid conductors the curves of Fig. 12 are represented by the equation $V = 36.7 \log_{10} D - 700\, d \log_{10} d - 90$, where D is the distance between conductors in inches and d is the diameter of the conductors in inches. This is a rather surprising result as the theoretical equation may be written as follows:

$$V = M\, d \log D - N\, d \log d + P$$

M, N and P being constants. With the exception of the first term this theoretical equation agrees with the equation representing the curves of Fig. 12.

The constants in the case of stranded conductors have not been worked out but by using the curves of Fig. 12 and interpolating we find that the critical voltage for No. 1 B. & S. cables (124 in. apart) is 106 kilovolts.

The curves of Fig. 12 refer to a barometric pressure of 29.5 in. (750 mm.) while the tests of the Denver-Boulder line were taken at an average pressure of 24.6 in. (614.7 mm.). We should then expect a critical voltage of the Denver-Boulder line of $106 \dfrac{24.6}{29.5}$ = 88.5 kilovolts, instead of 92.5 as given by the curve of Fig. 9.

That the critical voltage is proportional to the atmospheric pressure is generally admitted. However, the opportunity presented itself to repeat at Leadville (altitude 10,500 ft., 3,200 m.) some simple corona tests, which were performed a year before at Pittsfield and are described in the paper by Mr. Moody and the writer published in the TRANSACTIONS of the A. I. E. E., 1909.

Brass rods of different diameter were suspended parallel to a plate at a distance of 12 in. (30.4 cm.) between the center of the rod and the plate, and the voltage at which visible corona appeared was recorded.

Utmost care was taken to reproduce in Leadville the identical conditions under which the tests were taken at Pittsfield, and oscillograms of the e.m.fs. in both cases gave sine waves. The following table gives the results obtained at Pittsfield and Leadville and the ratios between the two critical voltages.

Diameter of rod	Kilovolts at Pittsfield	Kilovolts at Leadville	Ratio
$\frac{1}{8}$ in.	38	29.6	1.28
$\frac{1}{4}$ "	57	45	1.27
$\frac{3}{8}$ "	75	57.2	1.31
$\frac{1}{2}$ "	90.7	66.6	1.36

The barometric pressure was 29 in. (736 mm.) at Pittsfield and 20.2 in. (513 mm.) at Leadville. The temperature was 59 deg. fahr. at Leadville and 80 deg. fahr. at Pittsfield.

The correction coefficient suggested by Ryan is $\frac{b}{459+t}$ where b is the barometric pressure in inches and t is the temperature in degrees fahr. Using the values of pressure and temperature corresponding to the tests at Leadville and Pittsfield, Ryan's formula gives as ratio between the two critical voltages

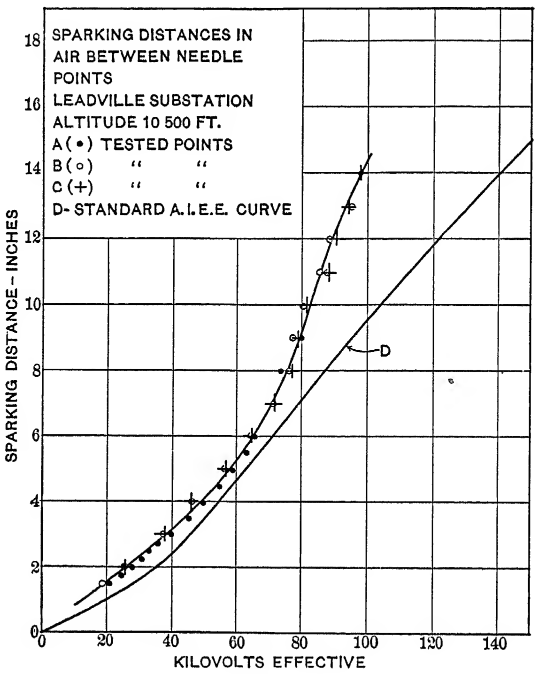


FIG. 13

1.38. The complication introduced in the measurements by the temperature makes it impossible to reach any conclusion as to the exact influence of altitude.

Some spark tests were also taken at Leadville and the results are plotted in Fig. 13. These tests were taken between sharp needle points, and the A. I. E. E. rule of keeping a distance twice the length of the gap between the gap itself and the nearest object, was strictly observed. The experiments were performed in the Leadville substation of the Central Colorado Power Com-

pany at an altitude of 10,500 ft. (3,200 m.). In Fig. 13 are plotted the original points taken on three different days. The tests *A* were taken under the following atmospheric conditions:

Barometric pressure	20.2 in. (513 mm.)
Temperature	64.5 deg. fahr.
Relative humidity	22.5 per cent

For the tests *B*

Barometric pressure	20.14 in. (510.5 mm.)
Temperature	56.5 deg. fahr.
Relative humidity	45.5 per cent

and for the test *C*

Barometric pressure	20.15 in. (512 mm.)
Temperature	65.5 deg. fahr.
Relative humidity	43 per cent

In Fig. 13 the standard curve of the A. I. E. E. is plotted so that the two curves may be compared.

Some three-phase tests were also taken on the Denver-Boulder section but they could be performed at one voltage only.

At 84.5 kilovolts between conductors the corona and insulator losses of the three-phase line were 20.7 kw. It is interesting to compare this value of the three-phase losses with the value of the single-phase losses at the same voltage to ground. The voltage to ground is 49 kilovolts and the single-phase losses for 98 kilovolts between conductors are 10.5 kw. For the same voltage to ground, the three-phase losses are then practically double the single phase losses, but it must be remembered that the three-phase losses were measured on 27.6 miles (44.4 km.) of line as represented in Fig. 3, while the single-phase line experimented upon consisted of two conductors 124 in. (3.14 m.) apart for a distance of 18.4 miles (29.6 km.) and 248 in. (6.28 m.) apart for the remaining 9.2 miles (14.8 km.).

The high corona losses shown by these tests are of theoretical interest only, as they do not affect the economical operation of the system. However, this investigation although limited and incomplete, points to the danger of corona losses assuming prohibitive values should any greatly increased operating voltages be attempted. Therefore, in addition to the further investigation necessary to establish the law for losses on transmission lines and for the critical voltage of corona, it would appear that there is a field for considerable thought and experiment along the line of developing some efficient means of limiting the losses to permissible values.

Discussion on "Design, Construction and Tests of an Artificial Transmission Line", "Protection of Electrical Transmission Lines", "Tests of Arcing Ground Suppressors on the 40,000-Volt System of the Southern Power Co.," "Tests of Losses on High Tension Lines." Schenectady, February 15, 1911.

Ralph D. Mershon: There are one or two questions I would like to ask. One is with reference to the method of measurement of the line voltage which assumed the constancy of the ratio of the step-up power transformer. I wonder how accurate it was. A small error in voltage in some of the measurements would make a considerable amount of difference in the loss curves, and there is a chance for distortion of wave, other modifications of voltage, due to reactions in the transformer, producing a change of ratio.

Another statement appears which raises a somewhat similar question as to the wave form impressed on the line, and the possibility there was for distortion. This, of course, is a question similar to the previous one in regard to measurement. In the case of Fig. 4, it would be interesting to know where the charging current to the line was measured. I do not see that there is any statement made as to whether it was made on the low voltage side of the transformer or in the line itself. The average atmospheric conditions of the tests of curve *B* Fig. 4 of the other curves are given. It would have been an addition to the paper, I think, if the individual readings for some of the points on the curves were given. Additional information bearing on this matter has been given me by Mr. Faccioli as applied to Fig. 9. He says that the vapor product applying to that curve varied from 0.11 to 0.274. It is brought out in my Niagara paper that for low value of vapor product the variation in the losses with vapor product are not considerable, not such as would ordinarily attract attention, and it was because of that, I think, that I did not notice them at all in my Telluride measurements. It is only when you get above these values, as I remember it in the neighborhood of 0.3 and 0.4, that the effect of the moisture in the atmosphere becomes marked.

This low value of the vapor product might or might not account for lack of variation in visible corona with variation of atmospheric conditions. It would seem from the tests made so far by Mr. Faccioli that possibly the visible corona is not affected by humidity conditions but as I think I have said once or twice before, the critical point as I define it, is not the point at which corona begins, but at which the loss curve turns sharply upward.

Mr. Faccioli has determined that according to my Niagara data, the critical voltage of the Denver-Boulder line, should be 88.5 kilovolts. Unfortunately, Fig. 9 has not a sufficient amount of the lower part of the curve for the accurate application of my method. But my estimate for that curve, such as there

is of it, is that by my method the critical voltage would be about 87 kilovolts, which is not so far out from the value Mr. Faccioli obtains. The curve of Fig. 9 is the result of differences of two sets of measurements. The subtraction method may lead to errors of considerable magnitude especially in the lower part of the curve, resulting in considerable variation in the curve one way or the other. I think it hardly fair, therefore, to give this curve much weight in any critical discussion of either my method of obtaining the critical point or my results.

There is another question I would ask in regard to where the wattmeter was used with the coil directly in the high voltage circuit. What was the possibility of electrostatic effects affecting its reading?

The method of analysis Mr. Faccioli has adopted for determining the critical point does not appeal to me much. You first get a set of observations in which there is more or less error. You draw in the most probable curve. Then you get an empiric formula for the top part of the curve as closely as you can; more or less error there. Then by means of this formula you extend the upper limb of the curve down to the voltage axis, find the intersection and call that the critical point. It seems to me my method is much quicker, safer and much more rational especially as I do not agree in the use of the square law for the upper part of the curve. Although the square law may appear to apply, it seems to me there is every reason why it actually should not apply. For, if we are dealing with a sine wave voltage the loss above the critical point should be some function of that part of the area of the wave included between the two values of critical voltage. Therefore this loss cannot, rationally, follow the simple law of squares. As a matter of fact, if you derive the expression for the effective voltage of that part of the sine wave included between the two values of critical voltage, assume it to be acting against the critical and through a resistance and derive a curve connecting total impressed voltage and loss, you get a curve which has a shape closely approximating that of the actual loss curves obtained.

Mr. Faccioli says: "The law which gives the critical voltage at which corona appears in function of the diameter of the conductors and the distance between conductors is $V = M\, r \log D/r$, where M is a constant depending upon the barometric pressure and temperature, D is the distance between the centers of the conductors, r the radius of the conductor." I thought that expression was the expression giving the rate of fall of potential at the surface of the conductor, and that Professor Ryan had demonstrated pretty thoroughly that that was not the law which governed the beginning of corona, and that that is the reason why these curves do not follow the theoretical law as pointed out by Mr. Faccioli. They do, however, follow the empirical formula which I gave in my paper which is not, however, independent of diameter.

This question of the vapor product and its effect is something I have been looking for very interestedly in the further measurements of others. So far no one else seems to have gotten it. Referring to Mr. Creighton's paper, I hope that Mr. L. C. Nicholson who is here will tell us about work he has been doing independently along the same lines, and some of the results he has obtained.

Charles S. Ruffner: The measured losses referred to in the paper occur when the receiving end of the line is open circuited, and are greatly reduced when the load is delivered, or even when unloaded substation transformers are connected. That these losses are not serious in service is shown by the meter readings for the year. During 1910 88.2 per cent of the number of kilowatt hours generated was delivered to the low tension side of the substation transformers; that is, 11.8 per cent of the energy generated was used in station auxiliaries or lost in step-up transformers, transmission line and substation transformers. It is probable that less than 6/10 of this total loss should be charged to the line, so that the loss, in line only, amounts to about 7 per cent of the energy generated.

On account of the difficulty of measuring the potential at the receiving end of the line at open circuit, the effective value and wave form of the voltage is unknown under these conditions, but it is probable that the effective voltage is 25 per cent higher than at the generating station. It is also probable that in the section of line farthest from the generating station the distortion of the voltage wave may greatly increase the losses during part of the cycle above the loss that would correspond to the same effective voltage with a sine wave. At least it is possible that over some intermediate section of the line where the effective value of the voltage is insufficient to produce excessive loss, there may still be parts of the distorted voltage wave sufficiently above this critical voltage to cause excessive losses during part of the cycle. This would give greater losses at any measured effective voltage than those calculated for sine waves.

An interesting point that cannot be determined from the data at hand is suggested by the distortion of the wave of charging current, which, under some conditions, may approximate triple frequency. This may have an appreciable effect on such losses as are connected with inductive effects. That is to say, there may be a question whether the calculated ohmic losses, which have been subtracted from the measured total open circuit loss, should not be modified because of the change in current distribution in the circuit caused by this higher frequency current. If there is any such effect, the resulting values of "corona and insulator losses" given by such subtraction might include other losses. However, the fact that the greatest losses occur in the parts of the line farthest from the generating station shows that the loss is almost altogether a function of the voltage.

It is unfortunate that there is not available an oscillogram of

the voltage wave at the open end of the line when no transformers are connected. The importance of this is evident when, under normal voltages at Shoshone, the power required for the total line is about 2,300 kw. at open circuit and is reduced to about 1,300 kw. by connecting unloaded transformers to the line at Denver and at Boulder.

L. C. Nicholson: Professor Creighton mentions three foes to the continuity of service on a long distance transmission line; first, direct lightning stroke shattering insulators, second, induced effects from nearby lightning which may cause insulators to flashover, and third, outside interference. Mr. Mershon promises an insulator which will relish the direct stroke, and Professor Creighton tells us how to get rid of flashovers on one wire at a time so as to obviate consequent damage to insulators and conductors. No one is bold enough to suggest a cure for outside interference.

Professor Creighton explains why flashovers should occur on only one wire at a time. However, flashovers do not occur always as they should, and frequently involve two and sometimes three phases simultaneously. Our experience with these matters indicates that 60 per cent of all lightning disturbances are two-wire short circuits, that is, two insulators on different phases arc over simultaneously, 30 per cent are single insulator flashovers, that is, from one wire to ground, and 10 per cent are three-phase short circuits caused by simultaneous flashing of insulators on all three phases. Experience further indicates that the single-insulator flashovers involving limited current, usually go out after a few seconds, and do no considerable damage. Hence an arc suppressor to be of maximum benefit should provide for suppressing phase to phase arcs as well as phase to ground arcs.

Apparatus is in operation on the lines of the Niagara, Lockport & Ontario Power Co., to extinguish arcs occurring from line to ground and between phases and to accomplish this result in so short a time that synchronous receiving apparatus remains in step and thus avoid shutdowns. This apparatus consists essentially of enclosed fuses connected to the lines by means of quick acting air switches actuated by excess current in the line wires. The fuses act to shunt the primary short circuit on the lines and thus extinguish the arc. The switches are selective and short circuit by fuses the phase or phases which are already short circuited by the flashover arc or arcs. The fuses consist of No. 14 B. & S. copper wire contained in a paper tube 6 ft. long. The entire operation of throwing the fuses on the circuit and burning them out consumes less than 1/5 of a second. This short time is too small to throw heavily loaded synchronous motors or rotary convertors out of step. In fact the disturbance to the system is barely noticeable. Single-phase oil switches have been tried for this purpose, but we found them too slow to close and in great danger of exploding when opening heavy short circuit current, which amounts to 2,000 amperes or more.

Taylor Reed: In the papers which have been presented this evening there has been quite a wide application of the oscillograph in the observations made, ranging all the way from comparatively laboratory conditions in Professor Cunningham's paper to quite trying, what you may call road conditions, in Mr. Faccioli's paper. I would like to speak more particularly with reference to the oscillograph observations in Mr. Faccioli's paper. The oscillograph is usually considered quite a delicate instrument, but I think it is used under conditions there which quite demonstrate its practicability. The particular instrument in use was not a new one by any means, it had seen some pretty severe service under factory conditions. It was taken out to quite a number of remote points, where the matter of accident was serious, and where the matter of repairs was very formidable. Where appliances were very meagre it was shipped about a number of times, half a dozen or more, from one point to another. It was used under all sorts of crude conditions and the films were developed under such circumstances and with such appliances as could be got together at the various points of observation. Further in some of the observations it was necessary, as I understand, to relay the signals for the switch operation through two or three persons at the observing end, through more than a hundred miles of private telephone line, and through two or three persons at the switch end, and yet the observations were obtained with an exposure of the film of only a very few seconds, two or three or four seconds. I may say that the instrument as sent out was not in all particulars adapted to the purpose—the observer put on it, with such appliances as he had available, the necessary additional apparatus, to use very much longer films than had been provided, etc., showing a capability and resourcefulness of the oscillograph operator in the matter of taking observations, of which we have had altogether too little. The oscillograph in its development was brought into actual practical use by practical necessities rather than for academic purposes, but when it was prepared, however, and offered for use, it was taken up and adopted more immediately in academic quarters than in practical operating quarters, after which followed its adoption quite extensively for more practical operating purposes, and it is now distributed fairly widely for these purposes. I am sorry to say that I think a good many of the pieces of apparatus turned out for academic purposes have gone into glass cases and for the most part reposed there for show purposes, and I think that those which have been applied to operating conditions have been much more satisfactorily used.

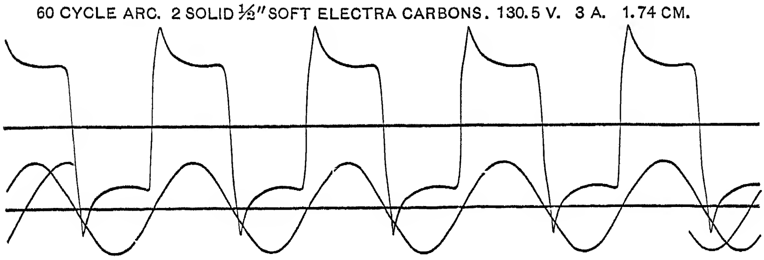
J. L. R. Hayden: In the latter part of Professor Creighton's paper two important and little understood phenomena are discussed, the time lag of the dielectric spark and the time lag of the arc.

The industrial importance of the dielectric spark lag is obvious when seeing the enormous transient voltages which are re-

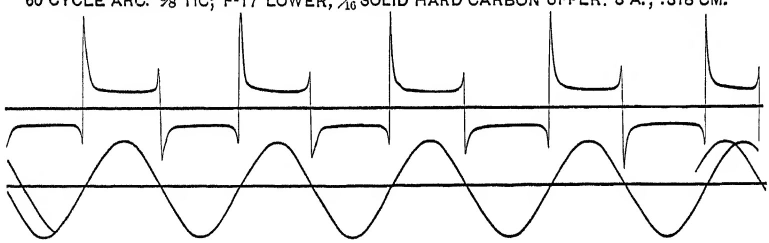
quired to break down even a short gap. Still less is known on the time lag of the arc. We have very complete data on the electrical characteristics of the arc under stationary conditions, largely from the work of Dr. Steinmetz, but very little on the transient phenomena of the arc.

Some years ago when developing the mercury arc rectifier we tried to find the time lag of the formation of the mercury arc by studying the time of overlap required for stability.

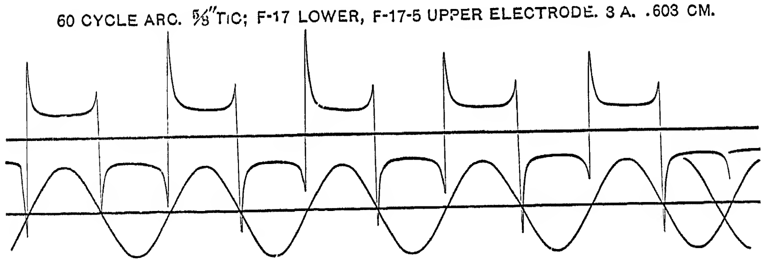
60 CYCLE ARC. 2 SOLID ½" SOFT ELECTRA CARBONS. 130.5 V. 3 A. 1.74 CM.



60 CYCLE ARC. ⅝" TIC; F-17 LOWER, 11/16" SOLID HARD CARBON UPPER. 3 A., .318 CM.



60 CYCLE ARC. ⅝" TIC; F-17 LOWER, F-17-5 UPPER ELECTRODE. 3 A. .603 CM.



In the mercury arc rectifier during every half wave the arc is formed by the dying out arc of the preceding half waves. By inductance the arcs are overlapped so as to maintain each arc until the next one is formed. By gradually reducing the inductance we tried to find the minimum overlap of the arc and from that the time required to start the arc. With currents of from 1 to 2 amperes and about 20 cm. arc length, this time was about one-thousandth of a second, but very much shorter with

larger currents and shorter arcs. We found that even minute traces of residual gases in the vacuum greatly retarded the formation of the arc so that the above values can be considered only as the upper limit of time.

Recently we have tried to investigate the same phenomenon by studying alternating arcs by oscillograph.

In stationary conditions maximum current gives minimum voltage in the arc.

Oscillograms of alternating arcs show the minimum voltage to take place later than the maximum current, and from this further investigation may give some data on the time lag of the arc.

The three oscillograms show this effect for an arc between soft carbons, an arc between two terminals of metallic titanium and an arc between one titanium and one hard carbon terminal.

F. W. Peek, Jr.: All corona measurements made on actual transmission lines are welcome and valuable additions to the data on this very important subject. Mr. Faccioli's measurements are particularly interesting because they were made on a line operating right at the *critical voltage*. It is difficult, however, to formulate laws governing corona loss from tests made on a line of this length, since, there are too many variables to correct for, as different elevations at different parts of the line, different temperatures and weather conditions along the line, different voltage at the two ends, etc.

Undoubtedly the best method to determine the laws governing corona formation is by means of investigations on a short experimental line erected to represent practical conditions, and to supplement these investigations by extensive laboratory work. We have for the past year or more been carrying on such a study. An experimental line was erected representing standard practice. An approximate sine wave voltage up to 250,000 was available, and means were arranged for varying the spacing, size of conductor, etc. It was also arranged so that work could be done under all sorts of fair weather and storm conditions. Power measurements were made directly on the high side, eliminating error due to transformer losses.

These investigations show that the loss varies directly as the square of the excess voltage over the *disruptive critical voltage*, and directly as a frequency. Thus:

$$p = a f \ (e - e_0)^2 \qquad (1)$$

where p = kilowatt loss.
e = kilovolts line.
c is a term varying with the size of the wire and spacing.
f = frequency.

e_0 we have called the *disruptive critical voltage*. e_0 is much lower than the *visual critical voltage*, e_v, for small conductors and approaches e_v in value for large conductors.

Theoretically no loss should occur below the *visual critical voltage*, e_v loss does occur, however, due to irregularities, dirt, etc., on the surface of the wire. For line voltages near e_0, the loss is greater than given by equation (1) for large wire, and less for small wires. This small excess loss is due to " dirt " and is apparently represented by:

$$p_1 = g\, e^{-h\,(e_0 - e)^2} \tag{2}$$

Curves taken over a very wide range show no change in e_0 due to humidity. Temperature changes show that e_0 varies inversely as the absolute temperature.

Snow, rain or sleet storms lower the voltage at which corona

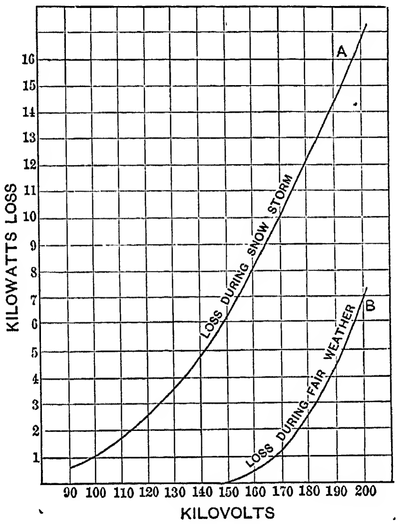


FIG. 1.—Corona loss

forms to a very great extent and increase the loss. Wet wires due to heavy fog also show a decided decrease in e_0. The effect of storms should be seriously considered in the design of transmission lines. Looking at Fig. 1: curve A shows the total measured loss during a snow storm, curve B shows the corresponding fair weather loss.

L. T. Robinson: With reference to the work these investigators have been able to do with the oscillograph, it seems to me that it is very unfortunate they have not been able to get better results, with what appears to me to be such a good tool; that is, I think it is extremely unfortunate that the apparent reproductions are not reproductions at all, but that they have been drawn, presumably with fidelity, but we do not know

that they have. It has nearly always been possible to get—I believe we have been able to demonstrate this without question —a good clear, definite, original reproduction that carries all the original data with it, I would like to take what little time is at my disposal in this discussion, to protest against the use of re-drawn oscillograph records where the originals can be used, which I believe is in almost every case, possible. If redrawing must be done, it should be done in a way so that it has no deception about it—that is, a black line on a white ground, showing that it is not an oscillograph record but something else. We would then avoid all complications, and if we saw one of these black lines on a white ground we would simply believe as much of it as we saw fit to. There are many points that may come up in checking records that are not of interest, perhaps, to the observer who makes the records at the time. If we reproduce the actual record it has the advantage of being there always, and some one who reads the paper at some later date may find something in it that entirely escaped the original observer. It is just the same as including the actual data on which the observations were based in connection with any curves that may be drawn—which was referred to previously—this I think should always be done. If the original data interferes with the smooth flow of the text it should be included in an appendix where any one who cares to verify the curves, etc., can refer to it at any time.

Chas. F. Scott: All these papers are exceedingly interesting as they deal with a subject of combined theoretical and research importance, which is also of very great practical importance. They attack the real problems in transmission work. Mr. Creighton's paper is one of the most comprehensive papers that has been presented dealing with the very great practical difficulties and problems in what is now the greatest factor in transmission work, the continuity of service. It not merely states a problem, but gives the solution of it also. The paper by Messrs. Burkholder and Marvin, dealing with tests on the Southern Power Company's line, in conjunction with the paper of Mr. Creighton, shows pretty conclusively the operation of this method under actual service conditions. We are fortunate to have presented from another source, a line of parallel work closely following the one explained by Mr. Creighton, which, as I understand, has been in use on the important and extensive lines of the Niagara, Lockport and Ontario Power Company. All this means progress, progress of the most substantial and best kind. It is the direct proof of what I was saying this afternoon as to the present attitude of the large manufacturing companies towards the practical operating problems. This is not directly a commercial problem of the manufacturing company, it is rather a problem dealing in the large and broad gauge way with the industry, by which electric service may be made more reliable, and after all it is the final object of all our work to give better service. The relation of the manufacturing company

towards this work is not a narrow commercial one, the problems are studied in the broadest way, and time and ability and money are directed towards their solution. All those engaged in high tension work will be much profited by the papers which have been presented here at this session.

G. Faccioli: I will answer quickly some of Mr. Mershon's questions. The volts were measured on the secondary of the step-up transformer. The transformer was a 2,500-kw. transformer, and the voltage was measured on the secondary side. However, some of the tests were checked by using a spare 2,500 kw. transformer as a potential transformer connected across the high tension line, and measuring the electromotive force on the low tension side of the transformer. This is a method which has been advocated this afternoon. The charging current was measured on the low tension side. It is not exactly the charging current, but the difference between the charging current and the exciting current of the transformer.

I do not think any conclusion can be drawn from my paper on vapor product, because the measurements of the atmospheric conditions were taken at one point of the line only.

Mr. Mershon says that the lower part of the curve might be in error, and that the method of determining the critical voltage by the point where the two curves meet is uncertain.

The method which I propose, to determine the critical voltage does not consist in taking the point where the two limbs of the curve meet, but in observing the point where the curve, given by the quadratic law, cuts the axis of the abscisse. I believe this method of determining the critical voltage is much more accurate and positive. Furthermore, the lower part of the curve may be uncertain, but no attempt was made to find an equation for it. At 97.5 kilovolts, where the quadratic law begins, the line losses were so much higher than the transformer losses, that the results appear reliable. Regarding electrostatic effects in the wattmeter, the current coil was connected to the potential coil to eliminate such effects.

E. E. F. Creighton: Although we are really retracing the oscillograms, we find we can better reproduce them by tracing them. We try to do it faithfully, and if we do miss anything, it is better to have the loss than to have oscillograms which you cannot read at all. I think the better way would be to print the oscillograms black on white, and get better results. I think that is being considered now by publishers. I want to express my appreciation of the work done by Mr. Nicholson. He certainly has added much to the value of the work in transmission line protection.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15-1911.

MECHANICAL FORCES IN MAGNETIC FIELDS

BY CHARLES P. STEINMETZ

1. General

Mechanical forces appear wherever magnetic fields act on electric currents. The work done by all electric motors is the result of these forces. In electric generators, they oppose the driving power and thereby consume the power which finds its equivalent in the electric power output. The motions produced by the electromagnet are due to these forces. Between the primary and the secondary coils of the transformer, between conductor and return conductor of an electric circuit, etc., such mechanical forces appear.

The electromagnet, and all electrodynamic machinery, are based on the use of these mechanical forces between electric conductors and magnetic fields. So also is that type of transformer which transforms constant alternating voltage into constant alternating current. In most other cases however, these mechanical forces are not used, and therefore are commonly neglected in the design of the apparatus, under the assumption that the construction used to withstand the ordinary mechanical strains to which the apparatus may be exposed, is sufficiently strong to withstand the magnetic mechanical forces. In the large apparatus, operating in the modern huge electric generating systems, these mechanical forces due to magnetic fields may however, especially under abnormal, though not infrequently occurring conditions of operation (as short circuits), assume such formidable values, so far beyond the normal mechanical strains, as to require consideration. Thus large transformers on big generating systems have been torn to pieces by

the magnetic mechanical forces of short circuits, cables have been torn from their supports, disconnecting switches blown open, etc.

In the following, a general study of these forces will be given. This also gives a more rational and thereby more accurate design of the electromagnet, and permits the determination of what may be called the efficiency of an electromagnet.

Investigations and calculations dealing with one form of energy only, as electromagnetic energy, or mechanical energy, usually are relatively simple and can be carried out with very high accuracy. Difficulties however arise when the calculation involves the relation between several different forms of energy, as electric energy and mechanical energy. While the elementary relations between different forms of energy are relatively simple, the calculation involving a transformation from one form of energy to another, usually becomes so complex, that it either can not be carried out at all, or even only approximate calculation becomes rather laborious and at the same time gives only a low degree of accuracy. In most calculations involving the transformation between different forms of energy, therefore it is preferable not to consider the relations between the different forms of energy at all, but to use the *law of conservation of energy* to relate the different forms of energy, which are involved.

Thus, when mechanical motions are produced by the action of a magnetic field on an electric circuit, energy is consumed in the electric circuit, by an induced e.m.f. At the same time, the stored magnetic energy of the system may change. By the law of conservation of energy, we have

Electric energy consumed by the induced e.m.f. = mechanical energy produced, + increase of the stored magnetic energy. (1)

The consumed electric energy, and the stored magnetic energy, are easily calculated, as their calculation involves one form of energy only, and this calculation then gives the mechanical work done, $= F\,l$, where F = mechanical force, and l = distance over which this force moves.

Where mechanical work is not required, but merely the mechanical forces, which exist, as where the system is supported against motions by the mechanical forces—as primary and secondary coils of a transformer, or cable and return cable of a circuit—the same method of calculation can be employed, by assuming some distance l of the motion (or dl); calculating the

mechanical energy $w_0 = F\,l$ by (**1**), and therefrom the mechanical force as $F = \frac{w_0}{l}$, or $F = \frac{d w_0}{d\,l}$.

Since the induced e.m.f., which consumes (or produces) the electric energy, and also the stored magnetic energy, depend on the current and the inductance of the electric circuit, and in alternating-current circuits the impressed voltage also depends on the inductance of the circuit, the inductance can frequently be expressed by supply voltage and current; and by substituting this in equation (**1**), the mechanical work of the magnetic forces can thus be expressed, in alternating-current apparatus, by supply voltage and current.

In this manner, it becomes possible for instance to express the mechanical work and thereby the pull of an alternating electromagnet, by simple expressions of voltage and current, or to give the mechanical strains occurring in a transformer under short circuits, by an expression containing only the terminal voltage, the short-circuit current, and the distance between primary and secondary coils, without entering into the details of the construction of the apparatus.

This general method, based on the law of conservation of energy, will be illustrated by some examples, and the general equations then given.

2. The Constant Current Electromagnet

Such magnets are, for instance, the series operating magnets of constant current arc lamps on direct-current and alternating-current circuits.

Let i_0 = current, which is constant during the motion of the armature of the electromagnet, from its initial position 1, to its final position 2, l = the length of this motion, or the stroke of the electromagnet, in cm., and n = number of turns of the magnet winding.

The magnetic flux Φ, and the inductance

$$L = \frac{n\,\Phi}{i_0}\,10^{8} \tag{2}$$

of the magnet, vary during the motion of its armature, from a minimum value,

$$\Phi_1 = \frac{i_0\,L_1}{n}\,10_8 \tag{3}$$

in the initial position, to a maximum value,

$$\Phi_2 = \frac{i_0 \; L_2}{n} 10^8 \tag{4}$$

in the end position of the armature.

Hereby an e.m.f. is induced in the magnet winding,

$$e' = n \frac{d \, \Phi}{d \, t} 10^{-8} = i_0 \frac{d \, L}{d \, t} \tag{5}$$

This consumes the power

$$p = i_0 \, e' = i_0^2 \frac{d \, L}{d \, t} \tag{6}$$

and thereby the energy

$$w = \int_1^2 p \, d \, t = n \, i_0^2 \, (L_2 - L_1) \tag{7}$$

Assuming that the inductance, in any fixed position of the armature, does not vary with the current, that is, that magnetic saturation is absent,* the stored magnetic energy is:

In the initial position, 1,

$$w_1 = \frac{i_0^2 \, L_1}{2} \tag{8}$$

in the end position, 2,

$$w_2 = \frac{i_0^2 \, L_2}{2} \tag{9}$$

The increase of the stored magnetic energy, during the motion of the armature, thus is

$$w' = w_2 - w_1 = \frac{i_0^2}{2} (L_2 - L_1) \tag{10}$$

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* If magnetic saturation is reached, the stored magnetic energy is taken from the magnetization curve, as the area between this curve and the vertical axis.

The mechanical work done by the electromagnet thus is, by the law of conservation of energy,

$$w_0 = w - w'$$

$$= \frac{i_0^2}{2} (L_2 - L_1) \text{ joules.} \tag{11}$$

If l = length of stroke, in cm., F = average force, or pull of the magnet, in grammes weight, the mechanical work is

$$F\,l \text{ g-cm.}$$

Since

$$g = 981 \text{ cm-sec.} \tag{12}$$

= acceleration of gravity, the mechanical work is, in absolute units,

$$F\,l\,g$$

and since one joule = 10^7 absolute units, the mechanical work is

$$w_0 = F\,l\,g\,10^{+7} \text{ joules.} \tag{13}$$

From (11) and (12) then follows:

$$F\,l = \frac{i_0^2}{2\,g} (L_2 - L_1)\,10^{+7} \text{ g-cm.} \tag{14}$$

as the *mechanical work of the electromagnet*, and:

$$F = \frac{i_0^2}{2\,g} \frac{L_2 - L_1}{l}\,10^7 \text{ g.} \tag{15}$$

as the average force, or pull of the electromagnet, during its stroke l.

Or, if we consider only a motion element $d\,l$;

$$F = \frac{i_0^2}{2\,g} \frac{d\,L}{d\,l}\,10^{+7} \text{ g.} \tag{16}$$

as the force, or pull of the electromagnet in any position l.

Reducing from g-cm. to ft-lb., that is, giving the stroke l in feet, the pull F in pounds, we divide by

$$454 \times 30.5 = 13{,}850$$

which gives, after substituting for g from **(12)**:

$$\textbf{(14)}: \quad F\,l = 3.68\, i_0^2\,(L_2 - L_1) \text{ ft.-lb.} \tag{17}$$

$$\textbf{(15)}: \quad F = 3.68\, i_0^2\,\frac{L_2 - L_1}{l} \text{ lb.} \tag{18}$$

$$\textbf{(16)}: \quad F = 3.68\, i_0^2\,\frac{d\,L}{d\,l} \text{ lb.} \tag{19}$$

These equations apply to the direct-current electromagnet as well as to the alternating-current electromagnet.

In the alternating-current electromagnet, if i_0 is the effective value of the current, F is the effective or average value of the pull, and the pull or force of the electromagnet pulsates with double frequency between 0 and 2 F.

In the alternating-current electromagnet usually the voltage consumed by the resistance of the winding, $i_0\,r$, can be neglected compared with the voltage consumed by the reactance of the winding, $i_0\,x$, and the latter, therefore, is practically equal to the terminal voltage e of the electromagnet. We have then, by the general equation of self-induction,

$$e = 2\,\pi\,f\,L\,i_0 \tag{20}$$

where f = frequency, in cycles per second.

From which follows,

$$i_0\,L = \frac{e}{2\,\pi\,f} \tag{21}$$

and substituting **(21)** in equations **(14)** to **(19)**, gives as the equation of the *mechanical work, and the pull of the alternating-current electromagnet.*

In the metric system;

$$F\,l = \frac{i_0\,(e_2 - e_1)\,10^7}{4\,\pi\,f\,g} \text{ g-cm.} \tag{22}$$

$$F = \frac{i_0\,(e_2 - e_1)\,10^7}{4\,\pi\,f\,g\,l} = \frac{i_0}{4\,\pi\,f\,g}\;\frac{d\,e}{d\,l}\,10^7 \text{ g.} \tag{23}$$

In foot pounds;

$$F\,l = \frac{.586\ i_0\ (e_2 - e_1)}{f}\ \text{ft-lb.} \tag{24}$$

$$F = \frac{.586\ i_0\ (e_2 - e_1)}{f\,l} = \frac{.586 i_0}{f}\ \frac{d\,e}{d\,l}\ \text{lb.} \tag{25}$$

Example.—In a 60-cycle alternating-current lamp magnet, the stroke is 3 cm., the voltage, consumed at the constant alternating current of 3 amperes, is 8 volts in the initial position, 17 volts in the end position. What is the average pull of the magnet?

$$l = 3 \text{ cm.}$$

$$e_1 = 8$$

$$e_2 = 17$$

$$f = 60$$

$$i_0 = 3$$

Hence, by (**23**):

$$F = 122 \text{ g. } (= 0.27 \text{ lb.})$$

The work done by an electromagnet, and thus its pull, depend, by equation (**22**), on the current i_0 and the difference in voltage between the initial and the end position of the armature, $e_2 - e_1$; that is, depend upon the difference in the volt-amperes consumed by the electromagnet at the beginning and at the end of the stroke. With a given maximum volt-amperes, $i_0\,e_2$, available for the electromagnet, the maximum work would thus be done, that is, the greatest pull produced, if the volt-amperes at the beginning of the stroke were zero, that is, $e_1 = 0$, and the theoretical maximum output of the magnet thus would be

$$F_m\,l = \frac{i_0\ e_2\ 10^7}{4\ \pi\ f\ g} \tag{26}$$

and the ratio of the actual output, to the theoretically maximum

output, or the efficiency of the electromagnet, thus is, by **(22)** and **(26)**,

$$\eta = \frac{F}{F_m} = \frac{e_2 - e_1}{e_2} \tag{27}$$

or, using the more general equation **(14)**, which also applies to the direct current electromagnet;

$$\eta = \frac{L_2 - L_1}{L_2} \tag{28}$$

The efficiency of the electromagnet, therefore, is the difference between maximum and minimum voltage, divided by the maximum voltage; or the difference between maximum and minimum volt-ampere consumption, divided by the maximum volt-ampere consumption; or the difference between maximum and minimum inductance, divided by the maximum inductance.

As seen, this expression of efficiency is of the same form as that of the thermodynamic engine;

$$\frac{T_2 - T_1}{T_2}$$

From **(26)** it also follows, that the maximum work which can be derived from a given expenditure of volt-amperes, $i_0\, e_2$, is limited. For $i_0\, e_2 = 1$, that is, for one volt-ampere, the maximum work, which could be derived from an alternating electromagnet, is, from **(26)**:

$$F_m\, l = \frac{10^7}{4\,\pi f . g} = \frac{810}{f} \text{ g-cm.} \tag{29}$$

That is, a 60-cycle electromagnet can never give more than 13.5 g-cm., and a 25-cycle electromagnet never more than 32.4 g-cm. pull per volt-ampere supplied to its terminals.

Or inversely, for an average pull of one g. over a distance of one cm., a minimum of $\frac{1}{13.5}$ volt-ampere is required at 60 cycles, and a minimum of $\frac{1}{32.4}$ volt-ampere at 25 cycles.

Or, reduced to pounds and inches:

For an average pull of one lb. over a distance of one in., at least 86 volt-amperes are required at 60 cycles, and at least 36 volt-amperes at 25 cycles.

This gives a criterion by which to judge the success of the design of electromagnets.

3. The Constant Potential Alternating Electromagnet

If a constant alternating potential e_0 is impressed upon an electromagnet, and the voltage consumed by the resistance, $i\,r$, can be neglected, the voltage consumed by the reactance x is constant and is the terminal voltage e_0, thus the magnetic flux ϕ also is constant during the motion of the armature of the electromagnet. The current i however varies, and decreases from a maximum i_1 in the initial position, to a minimum i_2 in the end position of the armature, while the inductance increases from L_1 to L_2.

The voltage induced in the electric circuit by the motion of the armature,

$$e' = n \frac{d\,\phi}{d\,t} 10^{-8} \tag{30}$$

then is zero, and therefore also the electrical energy expended;

$$w = 0$$

That is, the electric circuit does no work, but the mechanical work of moving the armature is done by the stored magnetic energy.

The increase of the stored magnetic energy is

$$w' = \frac{i_2^2 L_2 - i_1^2 L_1}{2} \tag{31}$$

and since the mechanical energy, in joules, is by (**13**),

$$w_0 = F\,l\,g\,10^{-7}$$

the equation of the law of conservation of energy,

$$w = w' + w_0 \tag{32}$$

then becomes

$$0 = \frac{i_2^2 L_2 - i_1^2 L_1}{2} + F l g \, 10^{-7}$$

or

$$F l = \frac{i_1^2 L_1 - i_2^2 L_2}{2 g} 10^7 \text{ g-cm.} \tag{33}$$

Since, from the equation of self-induction, in the initial position;

$$e_0 = 2 \pi f L_1 i_1 \tag{34}$$

in the end position;

$$e_0 = 2 \pi f L_2 i_2 \tag{35}$$

substituting (**34**) and (**35**) in (**33**), gives the equation of the constant potential alternating electromagnet.

$$F l = \frac{e_0 (i_1 - i_2)}{4 \pi f g} 10^7 \text{ g-cm.} \tag{36}$$

and

$$F = \frac{e_0 (i_1 - i_2)}{4 \pi f g l} 10^7 = \frac{e_0}{4 \pi f g} \frac{d i}{d l} 10^7 \text{ g.} \tag{37}$$

or, in ft-lb.

$$F l = \frac{.586 \, e_0 (i_1 - i_2)}{f} \text{ ft-lb.} \tag{38}$$

$$F = \frac{.586 \, e_0 (i_1 - i_2)}{f l} = \frac{.586 \, e_0}{f} \frac{d i}{d l} \text{ lb.} \tag{39}$$

Substituting $Q = e i =$ volt-amperes, in equations (**36**) to (**39**) of the constant potential alternating electromagnet, and equations (**22**) to (**25**) of the constant-current alternating magnet, gives the same expression of mechanical work and pull:

In metric system,

$$F\,l = \frac{\Delta\,Q}{4\,\pi\,f\,g}\,10^7 \text{ g-cm.} \tag{40}$$

$$F = \frac{\Delta\,Q}{4\,\pi\,f\,g\,l}\,10^7 = \frac{1}{4\,\pi\,f\,g}\;\frac{d\,Q}{d\,l}\,10^7 \text{ g.} \tag{41}$$

In foot-pounds,

$$F\,l = \frac{.586\;\Delta\,Q}{f} \text{ ft-lb.} \tag{42}$$

$$F = \frac{.586\;\Delta\,Q}{f\,l} = \frac{.586}{f}\;\frac{d\,Q}{d\,l} \text{ lb.} \tag{43}$$

where $\Delta\,Q$ = difference in volt-amperes consumed by the magnet in the initial position, and in the end position of the armature.

Both types of alternating current magnet then give the same expression of efficiency;

$$\eta = \frac{\Delta\,Q}{Q_m} \tag{44}$$

where Q_m is the maximum volt-amperes consumed, corresponding to the end position in the constant current magnet, to the initial position in the constant potential magnet.

4. Short Circuit Stresses in Alternating Current Transformers

At short circuit, no magnetic flux passes through the secondary coils of the transformer, if we neglect the small voltage consumed by the ohmic resistance of the secondary coils. If the supply system is sufficiently large to maintain constant voltage at the primary terminals of the transformer even at short circuit, full magnetic flux passes through the primary coils.* In this case the total magnetic flux passes between

* If the terminal voltage drops at short circuit on the transformer secondaries, the magnetic flux through the transformer primaries drops in the same proportion, and the mechanical forces in the transformer drop with the square of the primary terminal voltage, and with a great drop of the terminal voltage, as occurs for instance with large transformers at the end of a transmission line or long feeders, the mechanical forces may drop to a small fraction of the value, which they have on a system of practically unlimited power.

primary coils and secondary coils, as self-inductive or leakage flux. If then x = self-inductive or leakage reactance, e_0 = impressed e.m.f., $i_0 = \frac{e_0}{x}$ is the short circuit current of the transformer. Or, if as usual the reactance is given in per cent, that is, the $i x$ (where i = full load current of the transformer) given in per cent of e, the short circuit current is equal to the full load current divided by the percentage reactance. Thus a transformer with 4 per cent reactance would give a short circuit current, at maintained supply voltage, of 25 times full load current.

To calculate the force F, exerted by this magnetic leakage flux on the transformer coils — (which is repulsion, since primary and secondary currents flow in opposite direction) we may assume, at constant short-circuit current i_0, the secondary coils moved against this force F, and until their magnetic centers coincide with those of the primary coils; that is, by the distance l, as shown diagrammatically in Fig. 1, the section of a shell type transformer. When brought to coincidence, no magnetic flux passes between primary and secondary coils, and during this motion, of length l, the primary coils thus have cut the total magnetic flux ϕ of the transformer.

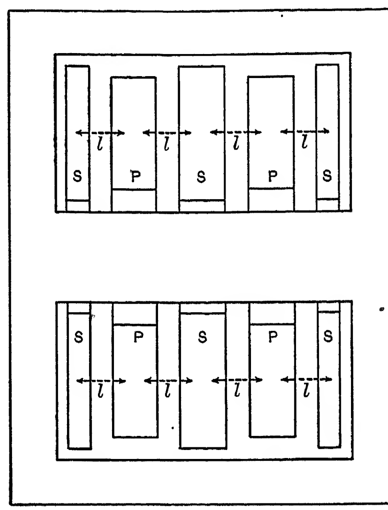


FIG. 1

Hereby in the primary coils a voltage has been induced,

$$e' = n \frac{d\,\Phi}{d\,t} 10^{-8}$$

where n = effective number of primary turns.

The work done or rather absorbed by this voltage e', at current i_0, is

$$w = \int e' i_0\, d\,t = n\, i_0\, \Phi\, 10^{-8} \text{ joules.} \tag{45}$$

If L = leakage inductance of the transformer, at short circuit, where the entire flux Φ is leakage flux, we have,

$$\Phi = \frac{L\, i_0}{n} 10^8 \tag{46}$$

hence, substituted in (45)

$$w = i_0^2 L \tag{47}$$

The stored magnetic energy at short circuit is

$$w_1 = \frac{i_0^2 L}{2} \tag{48}$$

and since at the end of the assumed motion through distance l, the leakage flux has vanished by coincidence between primary and secondary coils, its stored magnetic energy also has vanished, and the change of stored magnetic energy therefore is

$$w' = w_1 = \frac{i_0^2 L}{2} \tag{49}$$

Hence the mechanical work of the magnetic forces of the short circuit current is

$$w_0 = w - w' = \frac{i_0^2 L}{2} \tag{50}$$

It is, however, if F is the force, in g., l the distance between the magnetic centers of primary and secondary coils:

$$w_0 = F\, l\, g\, 10^{-7} \text{ joules.}$$

Hence

$$F\, l = \frac{i_0^2 L}{2\, g} 10^7 \text{ g-cm.} \tag{51}$$

and

$$F = \frac{i_0^2 L}{2\, g\, l} 10^7 \text{ g.} \tag{52}$$

the mechanical force existing between primary and secondary coils of a transformer at the short circuit current i_0.

Since at short circuit, the total supply voltage e_0 is consumed by the leakage inductance of the transformer, we have

$$e_0 = 2 \pi f L i_0 \tag{53}$$

hence, substituting (**53**) in (**52**), gives

$$F = \frac{e_0 i_0 10^7}{4 \pi f g l} \text{ g.}$$

$$= \frac{810 e_0 i_0}{f l} \text{ g.} \tag{54}$$

Example.—Let, in a 25-cycle 1667-kw. transformer, the supply voltage $e_0 = 5200$, the reactance = 4 per cent. The transformer contains two primary coils between three secondary coils, and the distance between the magnetic centers of the adjacent coils or half coils is 12 cm., as shown diagrammatically in Fig. 1. What force is exerted on each coil-face during short circuit, in a system which is so large as to maintain constant terminal voltage?

At 5200 volts and 1667 kw., the full load current is 320 amperes. At 4 per cent reactance the short-circuit current therefore $i_0 = \frac{320}{.04} = 8000$ amperes. Equation (**54**) then gives, for $f = 25$, $l = 12$;

$$F = 112 \times 10^6 \text{ g.}$$

$$= 112 \text{ tons.}$$

This force is exerted between the four faces of the two primary coils, and the corresponding faces of the secondary coils, and on every coil face thus is exerted the force

$$\frac{F}{4} = 28 \text{ tons.}$$

This is the average force, and the force varies with double frequency, between 0 and 56 tons, and is thus an enormous force.

Substituting $i_0 = \frac{e_0}{x}$ in (**54**), gives as the short-circuit force of an alternating current transformer, at maintained terminal voltage e_0, the value

$$F = \frac{e_0^2\, 10^7}{4\, \pi\, f\, g\, l} = \frac{810\ e_0^2}{f\, l}\ \text{g.}$$

That is, the short circuit stresses are inversely proportional to the leakage reactance of the transformer.

In large transformers on systems of very large power, safety therefore requires the use of as high reactance as possible.

5. Repulsion between Conductor and Return Conductor

If i_0 is the current flowing in a circuit consisting of a conductor and the return conductor parallel thereto, and l the distance between the conductors, the two conductors repel each other by the mechanical force exerted by the magnetic field of the circuit, on the current in the conductor.

As this case corresponds to that considered in section 2, equation (**16**) applies, that is;

$$(\mathbf{16}) \qquad F = \frac{i_0^2}{2\, g}\, \frac{d\, L}{d\, l}\, 10^7\ \text{g.}$$

The inductance of two parallel conductors, at distance l from each other, and conductor diameter l_d, is, per cm. length of conductor;

$$L = \left(4 \log \frac{2\, l}{l_d} + \mu\right) 10^{-9}\ \text{h.} \qquad (\mathbf{55})$$

Hence, differentiated;

$$\frac{d\, L}{d\, l} = \frac{4 \times 10^{-9}}{l}$$

and, substituted in (**16**);

$$F = \frac{i_0^2}{50\, g\, l}\ \text{g.} \qquad (\mathbf{56})$$

or substituting (**12**);

$$F = \frac{20.4\, i_0^2\, 10^{-6}}{l} \text{ g.} \tag{57}$$

If l = 150 cm. (5 ft.)

$$i_0 = 200 \text{ amperes.}$$

this gives

F = 0.0054 g. per cm. length of circuit, hence it is inappreciable.

If however the conductors are close together, and the current very large, as the momentary short circuit current of a large alternator, the forces may become appreciable.

For example, a 2200-volt 4000-kw. quarter-phase alternator feeds through single conductor cables having a distance of 15 cm. (6 in.) from each other. A short circuit occurs in the cables, and the momentary short-circuit current is 12 times full-load current. What is the repulsion between the cables?

Full load current is, per phase, 910 amperes. Hence, short-circuit current, $i_0 = 12 \times 910 = 10{,}900$ amperes. l = 15. Hence,

$$F = 160 \text{ g. per cm.}$$

Or, multiplied by $\frac{30.5}{454}$

$$F = 10.8 \text{ lb. per ft. of cable.}$$

That is, pulsating between 0 and 21.6 lb. per ft. of cable. Hence sufficient to lift the cable from its supports and throw it aside.

In the same manner, similar problems, as the opening of disconnecting switches under short circuit, etc., can be investigated.

6. General Equations of Mechanical Forces in Magnetic Fields

In general, in an electromagnetic system in which mechanical motions occur, the inductance L is a function of the position l during the motion. If the system contains magnetic material, in general the inductance L also is a function of the current i, especially if saturation is reached in the magnetic material.

Let, then, L = inductance, as function of current i and position l.

L_1 = inductance, as function of the current i, in the initial position 1 of the system.

L_2 = inductance, as function of the current i, in the end position 2 of the system.

If then Φ = magnetic flux, n = number of turns interlinked with the flux, the induced e.m.f. is

$$e' = n \frac{d\,\Phi}{d\,t} 10^{-8} \tag{58}$$

We have, however,

$$n\,\Phi = i\,L\,10^8$$

hence,

$$e' = \frac{d\,(i\,L)}{d\,t}. \tag{59}$$

the power of this induced e.m.f. is

$$p = i\,e' = i\frac{d\,(i\,L)}{d\,t}$$

and the energy

$$\begin{aligned} w &= \int_1^2 p\;d\;t = \int_1^2 i\,d\,(\,i\,L) \\ &= \int_1^2 i^2\;d\;L + \int_1^2 i\,L\,d\,i \end{aligned} \tag{60}$$

The stored magnetic energy in the initial position 1 is

$$w_1 = \int_0^1 i\,d\,(i\,L_1) \tag{61}$$

In the end position 2,

$$w_2 = \int_0^2 i\,d\,(i\,L_2) \tag{62}$$

and the mechanical work thus is, by the law of conservation of energy

$$w_0 = w - w_2 + w_1$$

$$= \int_1^2 i\, d\, (i\, L) + \int_0^1 i\, d\, (i\, L_1) - \int_0^2 i\, d\, (i\, L_2) \tag{63}$$

and since the mechanical work is

$$w_0 = F\, l\, g\, 10^{-7} \tag{64}$$

We have;

$$F\, l = \frac{10^7}{g} \left\{ \int_1^2 i\, d\, (i\, L) + \int_0^1 i\, d\, (i\, L_1) - \int_0^2 i\, d\, (i\, L_2) \right\} \text{g-cm.} \tag{65}$$

If L is not a function of the current i, but only of the position, that is, if saturation is absent, L_1 and L_2 are constant, and equation (**65**) becomes,

$$F\, l = \frac{10^7}{g} \left\{ \int_1^2 i\, d\, (i\, L) + \frac{i_1^2\, L_1 - i_2^2\, L_2}{2} \right\} \text{g-cm.} \tag{66}$$

a. If i = constant, equation (**66**) becomes:

$$F\, l = \frac{10^7}{g} \; \frac{i^2\, (L_2 - L_1)}{2}$$

(Constant-current electromagnet)

b. If L = constant, equation (**66**) becomes:

$$F\, l = 0.$$

That is, mechanical forces are exerted only where the inductance of the circuit changes with the mechanical motion which would be produced by these forces.

c. If $i\,L =$ constant, equation (**66**) becomes:

$$F\,l = \frac{10^7}{g} \frac{i\,L\,(i_1 - i_2)}{2}$$

(Constant-potential electromagnet.)

In the general case, the evaluation of equation (**66**) can usually be made graphically, from the two curves, which give the variation of L_1 with i in the initial position, of L_2 with i in the final position, and the curve giving the variation of L and i with the motion from the initial to the final position.

In alternating magnetic systems, these three curves can be determined experimentally by measuring the volts as function of the amperes, in the fixed initial and end position, and by measuring volts and amperes, as function of the intermediary positions, that is, by strictly electrical measurement.

As seen, however, the problem is not entirely determined by the two end positions, but the function by which i and L are related to each other in the intermediate positions, must also be given. That is, in the general case, the mechanical work and thus the average mechanical force, are not determined by the end positions of the electromagnetic system. This again shows an analogy to thermodynamic relations.

DISCUSSION ON "MECHANICAL FORCES IN MAGNETIC FIELDS", PITTSFIELD, FEBRUARY 15, 1911.

A. S. McAllister: The author has called attention to the error involved in dividing the difference in energies in two positions of a solenoid plunger by the distance it moved to determine the force acting upon the solenoid. He has also intimated, without stating directly, the cause for that error. The energy in the magnetic field is expressed as $\frac{1}{2} L I^2$. It is somewhat analagous, not to potential energy, but to kinetic energy, that is, not to $f l$, but to $\frac{1}{2} M V^2$. In dealing with potential energies, the energy in one position may be subtracted from the energy in another position, and the difference divided by the distance between the two positions then gives the force. However, in the case of the solenoid the two energies are the kinetic energy under one condition and the kinetic energy under another condition, and the movement of the plunger is merely an incident to the change in the condition. The energy in the magnetic field cannot be defined as $\frac{1}{2} L I^2$ unless L is constant, as is true for the air circuit, but is not true for the iron circuit. Therefore, the equation given by Dr. Steinmetz cannot be applied directly when iron is in the circuit; which means that the equations, if used, become very complicated. As a matter of fact it is preferable not to use the equation, but as the author indicates, resort to graphical or similar methods for determining the energies in the two positions or the change in the energy with the change in position.

G. Faccioli: The value of mechanical forces which act on transformers under short circuit conditions is enormous, as pointed out by Dr. Steinmetz. So the transformer which has enjoyed the reputation of having no movable parts presents to the designer a difficult problem, that is the problem of keeping the windings in place when a short circuit occurs.

This purpose may be accomplished by adopting for the windings an exceptionally strong mechanical structure and, in certain instances, by distributing uniformly the leakage flux through the width of the leakage path thereby distributing the mechanical forces evenly throughout the leakage area.

But on account of the magnitude of these forces it seems necessary to improve the conditions by reducing as much as possible the forces themselves.

These forces are proportional to the leakage flux and to the current.

The leakage flux is proportional to the applied e.m.f. and if we assume that the power behind a transformer is unlimited and therefore the voltage will be maintained at its full value under all conditions, it is impossible to reduce the value of the leakage flux. We can, however, reduce the current by increasing the reactance of the transformer.

For instance, if a transformer has two per cent reactance,

this means that two per cent of the full voltage will send full load current through the apparatus with its secondary short circuited. If we apply full voltage to the transformer 50 times full load current will flow.

We then have, for two per cent reactance, flux one, short circuit current fifty, force fifty times one equals fifty.

If we double the reactance and make it four per cent, then the short circuit current at full voltage is twenty-five times full load current or one-half the value with two per cent reactance. The flux is one as before, the short circuit current is 25, therefore the force is 25 times one equals 25 or one-half what it was in the preceding case.

By increasing the reactance of a transformer we decrease in inverse proportion the mechanical forces on the windings.

If the reactance is not all in the transformer as inherent reactance but is divided in two parts, one inherent in the transformer and the other external to the transformer, the conditions are somewhat different.

Let us assume two per cent reactance in the transformer and two per cent outside reactance, then the total reactance of the circuit is four per cent and the short circuit current is 25 times normal load current. This short circuit current flowing through the external reactance causes a drop of e.m.f. equal to two per cent times 25, equals fifty per cent normal electromotive force.

It follows that we apply to the transformer one-half only of the total voltage and that the leakage flux is reduced to one-half its full value. The force is then equal to one-half times 25 equals $12\frac{1}{2}$ as against 25 which was the value of the force when the four per cent reactance was all inherent reactance of the transformer.

It appears that by judicious use of reactance we may be able to improve short circuit conditions and to reduce the mechanical forces to a considerable extent.

Formerly in the days of small units and limited power the factor which controlled the amount of reactance in the transformer was the regulation. Now, with large units and enormous powers, another point of view is added, and that is the ability of a transformer to withstand short circuit.

As it is generally the case the design of the transformer must be a compromise, because while on one hand we should use low reactance to secure good regulation, on the other hand we need high reactance to limit the value of the short circuit current.

In large power transformers the ability to withstand short circuits is far more important to modern engineers than good regulation.

Cassius M. Davis: I wish to offer an explanation of the operation of a solenoid when used to actuate an oil switch by means of a toggle mechanism. The plunger of the solenoid acts on the middle joint of the toggle, moving it until the two arms are brought a little beyond the point where they are in the same straight line.

The electrical operation may be outlined by reference to Fig. 1. The plunger in its initial position gives the solenoid the inductance L_1, and the current, starting at time t_0, would rise along the transient curve i_1. After time t_1 the current has risen to produce sufficient flux to start the plunger and it begins to close the toggle. In doing so the inductance of the solenoid increases, and an increase of inductance means a decrease in the rate at which the current rises in the solenoid. Thus at t_1 the current begins to rise along another transient curve indicated by i_2. At t_2 the arms of the toggle have come into line which suddenly releases the load and the joint breaks back to lock the switch mechanism; the plunger then suddenly jumps to its final position reaching it at t_3, and with it the inductance increases from L_2 to L_3, which may mean an actual decrease of

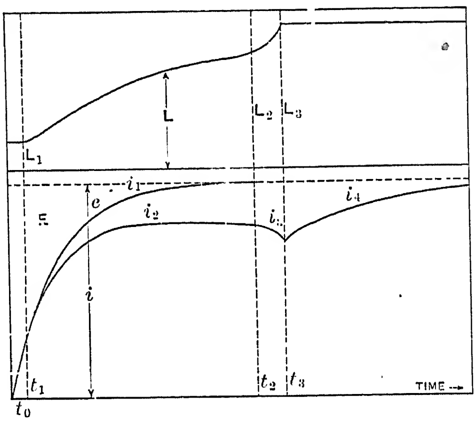


FIG. 1

current, indicated by i_3. From t_3 the current rises along a curve i_4 determined by L_3 and the current at time t_3.

The power at any instant is the product of the current and the induced voltage at that instant, and the induced voltage is proportional to the ordinates, e, above the curve; hence the energy consumed by the solenoid is the area product above and below the curve. Now the area above the curve is constant since the total voltage induced, E, is proportional to the total number of lines of force cut which is constant. Thus the work done by the electrical energy supplied depends only on the area under the curve, and hence the longer time the solenoid acts the more work it can do. The condition for maximum work may be represented by Fig. 2, where the current rises to nearly its final value before the plunger starts, which then moves in such a manner as to keep the current constant until the end of the motion.

This diagram will serve to derive an expression for the maximum work. The electrical energy consumed is

$$W = \int e\, i\, d\, t = i_0 \int e\, d\, t$$

but

$$\int e\, d\, t = E = \text{constant.}$$

Hence

$$W = i_0\, E = i_0\, n\ \phi\ 10^{-8} = i_0^2\, L$$

but the magnetic energy stored at the completion of the motion is

$$W_1 = \frac{i_0^2\, L}{2}$$

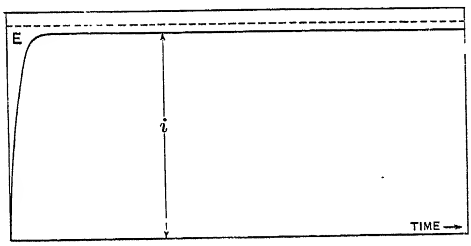


FIG. 2

Therefore the maximum mechanical work is

$$W_2 = W - W_1 = \frac{i_0^2\, L}{2}$$

which is one half of the electrical energy consumed; or the maximum efficiency of a solenoid is 50 per cent.

—— **Harper:** With particular reference to that portion of Dr. Steinmetz' paper which has to do with stresses in transformers, it will, perhaps, be interesting to present certain tests, the results of which are very gratifying indeed, and to discuss some of the peculiar conditions that are likely to exist in practice

The expression $F = \dfrac{810\, e_0\, i_0}{f\, l}$ g-cm., or $\dfrac{0.706\, e_0 i_0}{f\, l}$ in. lbs. formula (**54**) is readily verified by simple tests, performed with two similar coils, one being horizontally suspended directly over the other.

Two series of such tests were compiled some two years ago with arc light reactance coils, at Lynn and are shown here, tabulated. One set of tests shows an error of approximately $7\frac{1}{2}$ per cent, while the other gives an error of approximately $6\frac{1}{2}$ per cent.

It is seen that in both cases the calculated value is lower than the test value. This is probably due to the fact that the voltages have not been properly corrected for $I\ R$ drop.

Another series of tests were performed at Pittsfield some two months ago, the error of which is approximately $2\frac{1}{2}$ per cent. This value is well within the accuracy limits of the measuring apparatus.

The force thus determined, which may be called a horizontal force for convenience may, under certain conditions, be made up of components which are likely to be dangerous.

If, for instance, in that portion of the coils of shell type transformers which project beyond the core, the primaries are not directly opposite the secondaries, but have the effect of being staggered as shown, a couple exists, which tends to warp the coil. The centre line of magnetic gravity of the primaries is not in the same plane as the centre line of the secondaries. Hence, the resultant centre line, or direction of the force will not be horizontal, but will exist at an angle as shown in the figure.

Any coil carrying current will have a tendency to assume a circular shape. In shell type transformers, the legs of the coil are firmly held in position by the core, the ends, however, will tend to form of themselves semi-circles.

One other point to be considered is the tendency of a coil to form of itself a cable.

It should be remembered that the intensity of leakage flux is not uniform throughout the width of the coil, but is greater at the centre of the coil (if the coil be imbedded in iron). If then, a short circuit exist, the coil will have a tendency to buckle, and should it not be sufficiently strong to overcome this tendency, and its equilibrium be disturbed, the forces of conductor upon conductor (the value of which may be determined from formula (**57**) of Dr. Steinmetz' paper) will not lie in the same plane, and hence are liable to break the insulation tapings, and pile up on each other at the point of most intense density.

F. C. Green: A few instances of the effects of electromagnetic forces that have been observed in the practice of using transformers, will be given.

Seven or eight years ago some transformers returned from a large power plant, were observed to have the ends of the outside coils flared, as shown in Fig. 1. This was among the first instances to be brought to the attention of the designing engineers. To prevent the distortion of the coils at the ends, supporting strips were arranged as shown in Fig. 1. After the adoption of this construction no more trouble was experienced

with the flaring of the ends of the coils, but as the power installations became larger and larger, it was found that under short circuit conditions, the coils were entirely collapsed and twisted. The tendency seemed to be to make cable of the vertical portions of the coil. Mr. Harper pointed out that the portions of the coil outside of the iron tend to take a circular form under short circuit. No effect of this kind has been

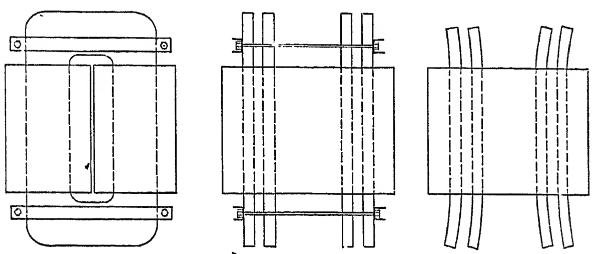


Fig. 1

noticed except at the corners of the coil. Here a number of instances of almost perfect circles of the copper conductor have been observed, the diameters of the circles being, however, from 1 in. to 2 in.

Nothing has been said about electromagnetic forces in core type transformers. The dotted lines (Fig. 2) show the position of the low tension coil and the solid lines show the position of the high tension coil. Under short circuit, according to the mathematics that have been developed, the force in this case is exerted horizontally, and there is little tendency to produce motion upward or downward. If we assume that the center of the primary coincides with the center of the secondary, then there can be no motion in the vertical direction, but it is found that considerable damage is done occasionally from the forcing of either the primary or secondary coil up into the iron. In most instances, the secondary is forced up. A better idea of the magnitude of electromagnetic forces is obtained in the destruction of core type transformers than in the destruction of the shell type, for the simple reason that while the core type coils are supposed to have their centers coincide approximately, they never do exactly, and so the force to produce vertical motion is exerted at such an angle as to make this force only a very small per-

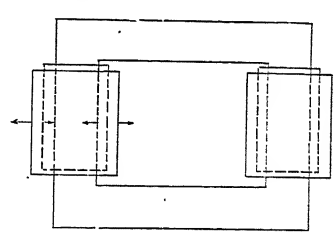
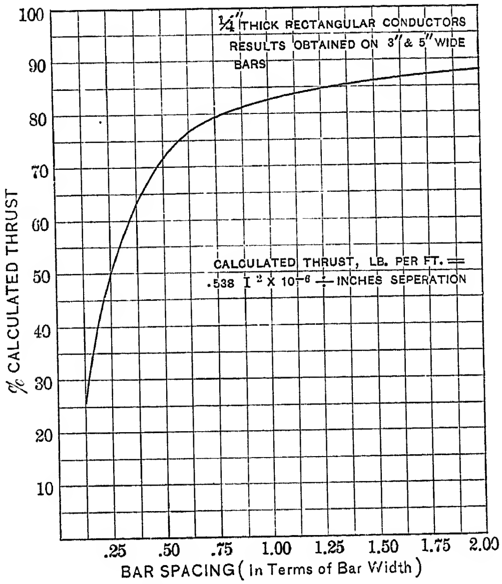


Fig. 2

Fig. 3

centage of the total force exerted between the primary and secondary. If the centers of the primary and secondary were exactly coincident the entire force would be exerted in a horizontal direction, and there would be no tendency for either coil to move vertically; but it seems that for mechanical reasons the secondary usually extends a little higher than the primary, resulting in the relation of forces indicated in Fig. 3. Of course whether the primary or secondary is forced up depends upon which one has its center line above the center line of the other.

C. J. Barrow: I wish to remark on the stresses between parallel conductors, Dr. Steinmetz considers the problem in his general solution. In this particular case it seems a little easier and more



Thrust on parallel conductors carrying current

direct to consider the stresses from the veiwpoint of the thrust on a current in a magnetic field. If we assume circular conductors and a field concentric about their centers, we can readily express the field at any point and calculate the thrust on a current in this field. The thrust on unit current (10 amperes) in a field of one line per sq. cm. is one dyne per cm. length of current acting normal to field and current. Working on this basis and converting to lbs., feet and amperes we get a formulae which exactly corresponds with that developed by Dr. Steinmetz based on the reactance of the conductors—lbs. per ft. $= 0.538\, I^2 \times 10.^{-6}$ divided by the separation of conductors centers in inches.

In the case of bus bars of rectangular section the forces are not

the same as for cylindrical conductors. The field is no longer concentric about central element, but elliptical with long axis of section as major axis of ellipse and the current acted on cannot now be approximately considered as concentrated at the center of conductor. Both considerations operate to reduce the forces exerted particularly between bars on short centers; the first by reducing the average field active, and the second by necessitating consideration of the thrust on a band of current the various elements of which are not all impelled in the same direction. In order to get a line of the corrections necessary on account of these considerations as well as to bolster up our faith in calculations of the forces present in high power bases under short circuit conditions, test determinations were made of the forces obtaining between 3 in. x $\frac{1}{4}$ in., and also 5 in. x $\frac{1}{4}$ in. bars arranged with faces parallel on various centers and at various currents. These tests made with direct currents ranging from 1000 to 8000 amperes, showed that forces varied as the square of the current and that with bars spaced on centers equal to the width of the bar about 80 per cent of the calculated forces obtained. At greater spacing larger values and at shorter spacings smaller values were found. Plotting results as per cent of calculated forces against spacing in terms of the width of bar used, the curves for 3 in. and 5 in. bars were found to coincide closely and it is felt that the curves obtained apply approximately to any width of bar. The results were obtained on bars $\frac{1}{4}$ in. thick. As bar thickness increases, cylindrical conductors are approached so with thicker bars somewhat higher results are to be expected.

Henry Pikler: In the present paper, also in some of the papers read yesterday, and in papers which will be read, there is much more said about forces in transformer's than we were accustomed to hear about in the past. What is the cause of this? Nothing else but that perhaps recently more transformers broke down, due to forces which arose in them created by short circuit which occurred on the secondary side of the transformer. Why do transformers go to pieces by such short circuits? We used to have transformers of small and also very large capacities in the past; we used to have very large power stations with so called unlimited power; why is it that at present transformers are more likely to be ruined by short circuits than in the past? The answer, to my mind, is this: The art of making insulating materials has advanced rather rapidly and the properties of insulating materials were greatly improved, the mechanical construction of the transformer, however, has not kept pace with it, particularly the mechanical construction of the windings and their supports. From the very extended discussion already heard, on this subject, it seems to me that we have all received the impression that the windings of a transformer, particularly of the type of transformers which were shown here, are very weak mechanically, and that their supports are also very weak. When the insulating materials are improved, the high

and low tension windings are brought closer together, consequently, the reactance of the transformer is diminished, and the forces arising on short circuits will be greatly increased. Hence, the weakness of the mechanical construction will be more apparent. Although it is very important to have a sufficiently high reactance in the transformer windings, this idea is not new —several years ago the results of investigations were published on this subject in the *Elektrotechnische Zeitschrift.** This idea was also embodied in transformers of large size with unlimited power behind, with successful results. The main trouble, as I see it, lies in the mechanical construction: The entire mechanical construction of the large shell type transformers, coils of which were exhibited here to-day, is such that it does not admit the proper supporting of the windings and does not permit of a solid interlocking between these windings, and the windings and core.

As to the calculation of these forces as given by Dr. Steinmetz, the derivation of the formulas is elegant, and the results are simple. The question is, however, whether they apply to actual conditions. I do not think they do. Those gentlemen who stated that they made actual tests and found that the results checked up very well with the formula given, I believe did not make those tests under actual operating conditions. I wish to ask if any of these gentlemen measured the forces in a transformer on a short circuit with unlimited power behind? I hardly think they did. An agreement with the formula was found as the result of tests made under conditions as may be found in the laboratory. If you take a transformer and short circuit it on one side and then gradually apply voltage to the other end until you reach any desired current, you will find that this current, which is called the short circuit current of the transformer, is proportional to the impedance voltage of the transformer. Also the forces will be found to be in proportion with the reactance, one of the components of the transformer. But when you have a transformer on the line, and *then* suddenly apply a short circuit on the secondary side, or you short circuit first the secondary side of the transformer and then suddenly switch the transformer to the line, you will find that the short circuit current and the forces arising in the transformer will be quite different from those given in the formula. These will depend upon the magnetic conditions of the transformer at the moment of the short circuit, that is the magnetic condition of the iron core and the relative phase relations of the current in the primary and secondary winding.

The analysis of the formula alone, as obtained by Dr. Steinmetz, is not sufficient for finding a remedy that will prevent the wrecking of the transformer windings by the forces arising on short circuits. It is necessary to go back to the derivation of the formula, to the place where Dr. Steinmetz allowed the coils

*Grosze Transformatoren für Electrochemische Zwecke, by Vanidzian —Jan. 24, 1909.

to move a certain distance in order to transform the potential energy into kinetic energy. Here is the salient point. The transformer must be constructed so as to preclude any such motion of the windings on short circuits.

John J. Frank: The reason the subject of stresses in alternating current transformers is of greater importance now than formerly is because ten or twelve years ago transformers were connected to lines in which the power back of them was relatively small. The recent combination of power plants into big systems gives practically an unlimited amount of power as far as small transformers are concerned. Small transformers which heretofore might have been rather weak in mechanical construction, but did stand up under short circuit conditions, are now not capable of doing it.

I do not believe that under actual operating conditions a break-down usually occurs the first time the strain is applied. A certain milling occurs in the core type as in the shell type, and it is only after repeated short circuits that the transformer fails and we get the twisting of the coils of the shell type transformer and the displacement of the coils of the core type transformer

Charles F. Scott: As remarked by the last speaker, the trouble is often not with the transformer, but with the power plant. In one case some large transformers were installed in a station of some 12,000 kw. and behaved beautifully for a number of years. They then began to break down, due to the fact that more generators had been added, and the short circuit currents were much larger. Although formulæ and diagrams are interesting, they do not give any adequate idea of what these forces are, compared with what one gains from an inspection of transformer coils which have been badly distorted. Coils of copper of large section bent around at sharp angles, and twisted up in great contortions, give an idea of a force away beyond our ordinary conceptions of the force of the magnetic field. I remember one case which I think is different from those mentioned, in which one part of a coil was peculiarly distorted. The coil was wound as a single layer of square wires about as large as one's finger—a part of the wires of the layer had been twisted and bent around in a most remarkable way, as part of the coil had slipped over on the other part. By a careful analysis of the position of the wires I found that a part of the primary coil had short circuited, and acted as a secondary in relation to the rest of the primary, setting up terrific forces within the coil itself, part acting as primary and part as secondary.

H. C. Cox: For the past eighteen months it has been the practice of the transformer testing department with which I am connected to subject all core type transformers of over 50 kw. capacity to a short-circuit test of five times rated current, applied suddenly on lowest tap connection through the make and break of an oil switch. During this period but one case (easily reme-

died by tightening coil supports) of coil displacement has been found.

Since the convention a 55 kw. transformer was subjected, out of oil, to twenty-seven times rated current without injury. Aside from heating and excessive vibration of core laminations no effect of the strain was apparent.

V. Karapetoff: Dr. Steinmetz's paper contains no literature references, nor does he give credit to previous investigators of the subject. Therefore, the following references may be of interest. His formula (**16**) has been known for at least twenty years; it can be found in the 1890 edition of Vaschy's "Traité d' Electricité et de Magnetisme", Vol. II, p. 35. For the principle upon which it is based see Maxwell's "Electricity and Magnetism", Vol. II, Art. 580.

The general theory and design of tractive electromagnets from the point of view of energy was given by Fritz Emde in his series of articles "Zur Berechnung der Elektromagnete" in *Elektrotechnik und Maschinenbau*, 1906, p. 945; also in the *Elektrotechnische Zeitschrift*, 1908, p. 817. He gives a proof of Kelvin's law that, when the currents in an electromagnetic system remain constant during a deformation of the system, the energy supplied by the sources of e.m.f. is divided equally, one half being converted into mechanical work, the other half increasing the stored magnetic energy of the system. From this law Steinmetz's equation (**16**) follows directly, because $\frac{1}{2} i_0^2 \, d L$ represents the increase in stored magnetic energy, and $F g \, d l$ is the mechanical work. Fritz Emde also proves that, when the flux does not change during the motion, the source of energy supplies only the $i^2 r$ loss. This theorem leads directly to equation (**33**) in Steinmetz's paper.

Emde's investigations have been lately taken up by Mr. E. Jasse (*Elektrotechnik und Maschinenbau*, 1910, p. 833) who has considerably simplified Emde's theory and applied the results to the calculation of performance of a number of commercial forms of electromagnets. Designers of electromagnets will find Jasse's articles very helpful in their work.

Mr. C. R. Underhill deserves considerable credit for a large number of tests on electromagnets. The results were published at different times in the *Electrical World*, and have been lately reprinted in his book entitled "Solenoids, Electromagnets, and Electromagnetic Windings". Professor Silvanus P. Thompson's pioneer work on electromagnets is well known. I wish only to mention his paper on the subject before the St. Louis International Electrical Congress in 1904; the paper will be found in Vol. I of the TRANSACTIONS of the congress.

The relation which connects the mechanical force between the windings of a transformer and its magnetic leakage is treated in Alex. Russell's "Alternating Currents", Vol. II, p. 234, in application to the theory of the constant-current floating-coil transformer. Russell's treatment is more correct than Dr.

Steinmetz's because the former considers an infinitesimal displacement of the coils, while Dr. Steinmetz bases his deduction upon a finite displacement until the two coils coincide.

Formula (**56**) for the repulsion between two conductors is as old as Monsieur André Marie Ampère (1775-1836), and in fact was first given by him. It can be derived in the C.G.S. system as follows: The flux density at a distance x from a straight infinite conductor carrying a current i is $B = 2\,i/x$ (law of Biot and Savart). According to Laplace's law the mechanical force is $F = B\,i\,l$, where l is the length of the second conductor. Hence, $F = 2\,l\,i^2/x$. It is hardly logical to derive this simple result from the variation of self-induction of the loop, because the expression for the inductance itself is originally derived from the law of Biot and Savart. The proof given in Steinmetz's paper will be found in Russell's "Alternating Currents", Vol. I, p. 63.

The preceding references are made not to detract from Dr. Steinmetz's work, but to place the proper credit where it belongs, and to enable those particularly interested in the subject to become oriented in the available literature. In this connection, I wish to make a general plea that papers presented before the Institute be provided with ample literature references, especially giving credit to foreign authors and to papers in foreign publications. The Board of Directors has lately made a highly commendable step in the direction of international courtesy and coöperation, by requiring the numerical values in the Institute papers to be given in the metric system. Requiring proper credit for priority in research and investigations would be in line with this amicable policy, and would greatly enhance the standing of our TRANSACTIONS abroad.

Considerable advantages would accrue to ourselves if the Institute papers were always provided with the most important literature references, namely

1. Repetition would be avoided, papers would be shorter, and the TRANSACTIONS less bulky.

2. Interest would be stimulated to reading or at least referring to many excellent standard works, at present hardly known at all among our engineers.

3. Study of a particular topic would be facilitated beyond the limits of a particular paper.

4. Each paper would be more liable to represent a truly new contribution to the subject, a contribution standing in a definitely stated relation to what is already known, instead of resembling sometimes a chapter from a text-book.

5. The spirit of coöperation would be more emphasized in which many investigators contribute their share to a complete solution of an engineering problem, instead of each working without due regard to the labors of others, duplicating their work, and thus making it extremely difficult for one to become oriented in the present status of knowledge in a particular topic.

K. Faye-Hansen: When dealing particularly with the short circuit stresses in alternating current transformers, Dr. Steinmetz has (without specially mentioning it) assumed that at constant current the force exerted by the magnetic leakage flux is the same for the whole distance of movement l until the magnetic centres of the coils coincide. This is however not correct as when the movement has gone so far that the current carrying parts of the two coils touch each other, the magnetic force against any further movement will be decreased. The short circuit stresses figured by Dr. Steinmetz are therefore too low (neglecting the error in decimals). I think that the subject can be handled equally correctly and simply by directly figuring the forces on the current carrying wires due to the magnetic field in the transformer under short circuit conditions. We find that the maximum force is equal to:

$$F = \frac{B}{2}\, n\, i_0 \sqrt{2}\, d\, \frac{10^{-1}}{981} \text{ grammes} \qquad (1)$$

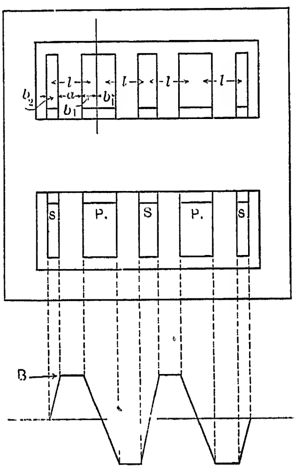


FIG. 1

Where B is the maximum induction in lines per sq. in. between the primary and secondary coils, and $\frac{B}{2}$ is the average of the (max.) induction through the coil: n the number of primary turns; i_0 the effective primary short circuit current in amperes and d the mean length of the turns in cm.

Assuming the form of field as shown in Fig. 1, the volts induced in the primary coils

$$e_0 = 4.44\, B \left(a + \frac{b_1 + b_2}{3}\right) d\, f\, n\, 10^{-8} \qquad (2)$$

The value for $B \times d \times n$ obtained by this is substituted in formula (**1**) gives:

$$F = \frac{i_0\, e_0\, \sqrt{2} \times 10^3 \times 10^{-1}}{981 \times 2 \times 4.44 \left(a + \frac{b_1 + b_2}{3}\right) f} \quad \frac{i_0\, e_0\, 1620}{f\left(a + \frac{b_1 + b_2}{3}\right)} \text{ grammes} \qquad (\mathbf{3})$$

While if the same dimensions and notations are brought into Dr. Steinmetz's formula No. 54 the result is

$$F = \frac{i_0\, e_0\, 1620}{f\left(a + \frac{b_1 + b_2}{2}\right)} \text{ grammes (the maximum force).}$$

It will thus be seen that the forces figured by Dr. Steinmetz may be as low as two-thirds of those figured under the assumption of the field form given above.

For the actual transformers the difference between the two methods of calculating will however be less than indicated above and usually in the neighborhood of 15 per cent to 25 per cent depending on the ratio between a and $(b_1 + b_2)$, *i.e.*, on the voltage, size and design of the transformer.

There is one more point to be remembered—the forces figured above are those which occur when the short circuit current of the transformers has reached its final value. The influence of current rushes however has been neglected. For the first cycles (according to the point of the voltage wave at which the short circuit is switched on)the current may be up to twice its final value and the forces equal to 4 times the value given in the formula.

The method given above for figuring the short circuit stresses in transformers has a further advantage over that given by Dr. Steinmetz—that an estimate of the forces due to the leakage lines bending over the coils can be made using formula (**1**) if only the lines of force are drawn in (as they would be expected to be) according to the relative size and position of the coils, and similarly an idea can be formed regarding which parts of the coils have to withstand the largest forces.

Dr. Steinmetz' conclusion that the short circuit stresses are inversely proportional to the leakage reactance of the transformer is on the face of it correct, but as the distance between the coils and thickness of them play an important part (as shown in the formula) regarding the forces and also influence the leakage reactance, it will be found that the forces really alter considerably more than in inverse proportion to the leakage reactance at given output, frequency, etc.

J. Murray Weed: For the mechanical forces in a transformer due to the magnetic leakage field, I have obtained results from the fundamental expression

$$S = \frac{B^2}{8\pi} \qquad (\mathbf{1})$$

which are identical with those which Dr. Steinmetz has derived. This expression gives, in dynes per sq. cm., both the stress of tension in a direction parallel to the field, and that of compression at right angles to the field. It is the stress at right angles to the leakage field which constitutes the pressure between primary and secondary windings in the transformer, and the approximate value of B which produces this stress may be calculated by the formula

$$B = \frac{\sqrt{2}\, 4\, \pi\, n\, I}{10\, l\, G} \tag{2}$$

where n is the number of turns in the transformer, I is the effective current, l is the length of the leakage path in centimetres and G is the number of groups of coils. A group of coils here signifies a portion of both primary and secondary windings, with equivalent numbers of turns, adjacent to each other at one surface only. The groups are assumed all equal, so that $n\, I/G$ is the number of primary or secondary amperes turns per group. Substituting the value of B, we have

$$S = \frac{4\, \pi\, n^2\, I^2}{100\, l^2\, G^2} \tag{3}$$

The area of the surface in which this stress is found is

$$A = (M\, L\, T)\, l \tag{4}$$

where $(M\, L\, T)$ is the mean length of turns. We have therefore, for the maximum force between adjacent primary and secondary coils

$$F_{max} = S\, A \tag{5}$$

$$= \frac{4\, \pi\, n^2\, I^2\, (M\, L\, T)}{100\, l\, G^2} \text{ dynes} \tag{6}$$

$$= 2.82\; 10^{-7}\, \frac{n^2\, I^2\, (M\, L\, T)}{l\, G^2} \text{ lbs.} \tag{7}$$

These equations give the force for any transformer having n turns, arranged in G equal groups, with a mean length of turn $(M\, L\, T)$ and a length of leakage path l, and with the current I flowing. The force increases with the square of the current, and will have its maximum value when the transformer is short circuited. If the primary terminal voltage is maintained, this

current is limited only by the impedance of the transformer, and if the reactance element of the impedance predominates, as it must do in order to give at the same time good efficiency and a proper limitation of the mechanical forces which we are considering, no important error will be introduced by substituting the reactance for the impedance. This reactance may be expressed in terms of the design characteristics of the transformer by means of a formula which, with various empirical modifications, is familiar to designers. Thus,

$$X = \frac{20\, f\, n^2\, A'}{10^8\, l\, G^2} \tag{8}$$

The short circuit current is, therefore

$$I_{(sc)} = \frac{E}{X} = \frac{10^8\, l\, G^2\, E}{20\, f\, n^2\, A'} \tag{9}$$

where A' is the effective combined area of the leakage paths in square inches and l is their length, in inches. If we express A' in terms of its two dimensions, this equation becomes

$$I_{(sc)} = \frac{10^8\, l\, G^2\, E}{20\, f\, n^2\, (M\, L\, T)\, w} \tag{10}$$

where w is the effective combined width of the leakage paths. It should be noted in equation (**7**) that, since we have one length on the numerator, $(M\, L\, T)$, and one in the denominator, l, these lengths may be expressed in inches instead of centimetres without affecting the result.

If we substitute the value of I from equation (**10**) for one of the factors in equation (**7**) we have

$$F_{max} = 1.41\, \frac{I_{(sc)}\, E}{f\, w} \tag{11}$$

In Dr. Steinmetz' equation (**54**), if we express F in pounds and l in inches, and divide by G to obtain the force acting on a single group, and then multiply by 2 to obtain the maximum force, we have

$$F_{max} = 1.41\, \frac{I_{(sc)}\, E}{f\, G\, d} \tag{12}$$

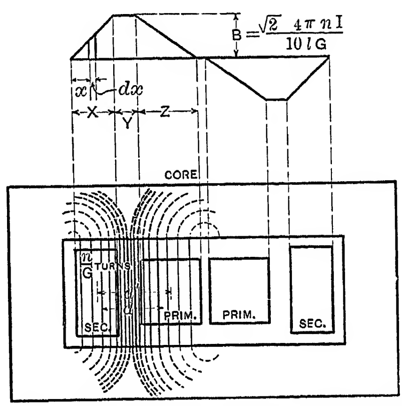
(If Dr. Steinmetz will pardon me for using the letter 'd' in the place of his 'l', I prefer to do this, because of the conventional use of 'l' for the length of the magnetic leakage path.)

If we write

$$w = G\, d \tag{13}$$

and this I think Dr. Steinmetz will grant me, equations (**11**) and (**12**) are the same. This says nothing however, for the accuracy of the assumptions made regarding the effective dimensions of the magnetic leakage field, since any errors in these assumptions eliminate themselves in the calculations. That it is impossible to assign specific dimensions to the leakage field, is illustrated by the easily recognized fact that the length of the leakage path is considerably greater for those portions of the windings which extend beyond the core in the shell type transformer than it is for those portions within the core.

The fact just stated results in a much reduced value of B for that portion of the windings which extend beyond the core,



SECTION THROUGH ONE HALF OF SHELL TYPE TRANSFORMER WINDING IN TWO GROUPS

and consequently in a very much reduced stress. In other words, those portions of the windings which extend beyond the core are not subjected to nearly such great stresses as those portions within the core.

If, now, we return to equation (**7**), and substitute from equation (**10**) for both the factors I, we have

$$F_{max} = 7.05\ 10^6\ \frac{l\, G^2\, E^2}{f^2\, n^2\, w^2\, (M\, L\, T)}\ \text{lbs.} \tag{14}$$

Equation (**14**) will be more useful to the designer than equation (**12**), since it shows the effects of changes in the design characteristics, including the number of primary turns, (if E is the primary voltage), the number of groups into which the windings are separated and the various dimensions.

Dr. Steinmetz' method of developing his equation (**54**) seems to involve the conception of a uniform force acting throughout the hypothetical motion of the coils. As a matter of fact, this force would be uniform, and maximum, from the time when motion begins until the adjacent boundaries come together, but would suffer a rapid reduction thereafter, until the centers of the coils coincide, when no force would exist. In order to obtain by equation (**54**) the value of the force active before motion begins (the actual force existing in the transformer), it is necessary to use a value for the length d (Dr. Steinmetz' "l"), which is less than the total distance between coil centers, and such that its product with the initial force will equal the summation of all the products of differential distances and their corresponding forces. This value of d may be determined from the derivation of the reactance formula.

If we multiply equation (**8**) through by I, and express A' in terms of its dimensions, we have

$$\text{React. } E = \frac{20\, f\, n^2\, I\, (M\, L\, T)\, (\overline{G\, d})}{10^8\, l\, g\, G^2} \tag{15}$$

This equation is derived as follows. Starting from the left hand end of the core window as illustrated in the figure, and passing through the windings toward the right, the density of the magnetic leakage flux may be plotted as illustrated by the curve at the top of the figure, if we assume a uniform distribution of ampere turns throughout the space occupied by the windings. Assuming that the return paths of the various portions of the leakage field are as represented in the figure, that portion of the flux which exists within the first group of the secondary windings cuts out and in from the left hand side. If B is the maximum flux density between the primary and secondary coils, the density of the elementary portion of flux, within the secondary group, of dimensions $(M\, L\, T)\, d\, x$, is $\frac{B}{X}\, x$.

And if $\frac{n}{G}$ is the number of turns in the group, the number of turns cut by this elementary portion of flux is $\frac{n}{G\, X}\, x$. Adding all the elementary products of flux by turns for that portion of the flux within the secondary winding, we have

$$\int_0^X \frac{B\, n}{G\, X^2}\, (M\, L\, T)\, x^2\, d\, x = \frac{B\, n}{G}\, (M\, L\, T)\, \frac{X}{3} \tag{16}$$

Integrating in a similar manner for that portion of the flux within the primary group, and expressing the result in equivalent secondary turns, we have

$$\frac{B\,n}{G}\,(M\,L\,T)\,\frac{Z}{3} \tag{17}$$

For that portion of flux which exists between the primary and secondary coils, the product of flux by turns is

$$\frac{B\,n}{G}\,(M\,L\,T)\,Y \tag{18}$$

the result being expressed in equivalent secondary turns for that portion of the flux which cuts through primary turns. Adding all these results, we have, for the entire group of primary and secondary coils

$$\frac{B\,n}{G}\,(M\,L\,T)\,d \tag{19}$$

where

$$d=\tfrac{1}{3}\,X+Y+\tfrac{1}{3}\,Z \tag{20}$$

The summation of flux turn linkages for the entire transformer is, therefore

$$\frac{B\,n}{G}\,(M\,L\,T)\,G\,d \tag{21}$$

Substituting this value in the fundamental voltage equation

$$E=\frac{\sqrt{2}\,\pi\,f\,N\,\phi}{10^8} \tag{22}$$

we have

$$\text{React. } E=\frac{\sqrt{2}\,\pi\,f\,n\,B\,(M\,L\,T)\,G\,d}{10^8\,G} \tag{23}$$

Substituting again for the value of B from equation (2), and expressing dimensions in inches, we obtain equation (15).

The development of formulæ similar to (**15**) have appeared in various text books, and it has been given here only for the purpose of finding the length of d, (Dr. Steinmetz' l), which he has called the distance between the magnetic centers, but which I would call the effective width of the magnetic leakage path for one group of coils. This has been found to be the distance between primary and secondary plus $\frac{1}{3}$ of the distance through primary, plus $\frac{1}{3}$ of the distance through secondary, which is less than the distance from coil center to coil center by $\frac{1}{6}$ of the distance through primary plus $\frac{1}{6}$ of the distance through secondary.

I should like to add, with reference to the formula for reactance, that various empirical modifications are in use, based upon different assumptions as to the dimensions of the leakage path. Also that the linkage of the secondary by leakage flux, as assumed by the return paths shown in the figure, has been questioned. I agree with those who criticize this assumption to the extent that for every linkage of leakage flux with the secondary there must be an equivalent linkage of the main flux in the opposite direction, and wherever these fluxes would occupy the same path, the evident result is the elimination of the secondary linkage. This condition does not exist throughout, however. Thus, for that portion of the winding of a shell type transformer which is outside of the core only the leakage flux exists, the main flux being confined practically to the core. It is a fact, however, that the reactance of the transformer, obtained from the integration of flux turn linkages, will be the same for the given distribution of leakage flux, whether the return paths are as shown in the figure, or all to the right, enclosing the primary.

H. B. Dwight (by letter): The following method of using a well-known equation to obtain some of the formulæ in Dr. Steinmetz' paper, may be interesting as an alternative proof.

The fundamental equation referred to is

$$F=\frac{H\,i}{10}\text{ dynes per cm. of conductor}$$

where H is the average magnetic field in which the conductor lies. This is proved by equating the mechanical work, $F\,d\,l$, to the electrical work, $\frac{i}{10}H\,d\,l$, when the conductor is moved a distance $d\,l$.

1. *Repulsion of Two Parallel Conductors.* The field around a long conductor is found by integrating the effect of the current on a unit pole at distance l from the wire, and is

$$H=\frac{2\,i}{10\,l}$$

The other wire lies in this average field, and the force per cm. on it is

$$F=\frac{H\,i}{10}=\frac{i^2}{50\,l}\text{ dynes}$$

$$=\frac{20.4\,i^2\,10^{-6}}{l}\text{ grams.}$$

2. *Short Circuit Stresses in a Shell Type Transformer.* During short circuit, the section of the path for the leakage flux is $m\,l$.

Where m = mean turn

$$l=a+\frac{b}{3}+\frac{c}{3}$$

a = distance between high and low tension coils.
b and c = widths of high and low tension half coils.

The density of the leakage lines is more accurately given by this value of l than by the distance between centers of half coils, which is $a+\frac{b}{2}+\frac{c}{2}$. The effective density of the leakage lines is

$$H=\frac{\phi}{l\,m}=\frac{e\,10^8}{2\,\pi\,T\,f\,l\,m}$$

where T = number of turns.

As the secondary part of a high-low group has a field H on one side, and zero field on the other, the mechanical force is that due to the average field $\frac{H}{2}$, and is

$$F=\frac{H}{2}\;\frac{i_0}{10}\;\frac{T\,m}{g\,K}\text{ grams}$$

where K = number of high-low groups
Therefor

$$F=\frac{e\,i_0\,10^7}{4\,\pi\,f\,g\,l\,K}\text{ grams}$$

which is the same result as in the paper.
From this

$$F = \frac{810\, e\, i_0}{f\, l\, K} \text{ grams}$$

which gives approximately 28 long tons for the example considered.

A. C. Zelewsky (by letter): I have read with great care the very interesting and important paper on "Mechanical Forces in Magnetic Fields" and would like to make a few remarks.

Within the last few years I have made, upon the suggestion of Mr. O. T. Bláthy, a considerable series of researches on the forces which act on the coils and conductors of machines during short circuit.

The general expression (**65**) of Dr. Steinmetz' paper for the mechanical work—or the mean force—and the derived formula (**66**) for absence of saturation, also do not seem to be expressed in the simple forms which they permit and which is a chief advantage of the other results of the paper.

By dealing first with the general system and considering the electromagnet, the transformer, and the parallel conductors only as special cases, a great deal of work may be saved. The mean force—or the mechanical work—are seldom of great interest, because generally the force for a special position or the maximum value of the force have to be determined.

Considering a differential motion of the system, the mechanical work done is

$$F\, d\, l \text{ ergs;} \tag{1}$$

the increase of stored energy is

$$\frac{d}{d\, l} \left\{ \int_0^i i' \frac{\delta\, \varphi'}{\delta\, i'}\, d\, i' \right\}\, d\, l \text{ ergs;} \tag{2}$$

and the electric energy absorbed by the induced electromotive force is

$$-i\, \frac{d\, \varphi}{d\, l}\, d\, l \text{ ergs;} \tag{3}$$

where F is the force exerted, l is the distance in the direction of motion, i and φ are the current and flux (or flux-turns) respectively during the motion, and i' and φ' are general values of current and flux (or flux-turns) respectively as they would increase together from zero to the limits i and φ—all quantities being expressed in c.g.s. units. Applying the law of conservation of energy,

$$F = i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left\{\int_0^i i'\,\frac{\partial\,\varphi'}{\partial\,i'}\,d\,i'\right\} \text{ dynes,} \tag{4}$$

which is equivalent to (**63**) of the paper.*

Another form of this equation can be derived by partial integration:

$$F = i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left|i'\,\varphi'\right|_0^i + \frac{d}{d\,l}\left\{\int_0^i \varphi' d\,i'\right\},$$

$$= i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}(i\,\varphi) + \frac{d}{d\,l}\left\{\int_0^i \varphi'\,d\,i'\right\},$$

$$= -\,\varphi\,\frac{d\,i}{d\,l} + \frac{d}{d\,l}\left\{\int_0^i \varphi' d\,i'\right\} \text{ dynes.} \tag{5}$$

Both equations for F are quite general, as nothing has been said about saturation and both i and φ are supposed to change during motion. In practical units they are

$$F = 0.102\left[i\,\frac{d\,\varphi}{d\,l} - \frac{d}{d\,l}\left\{\int_0^i i'\,\frac{\partial\,\varphi'}{\partial\,i'}\,d\,i'\right\}\right] 10^{-6} \text{ kg.;} \tag{6}$$

and

$$F = 0.102\left[-\,\varphi\,\frac{d\,i}{d\,l} + \frac{d}{d\,l}\left\{\int_0^i \varphi'\,d\,i'\right\}\right] 10^{-6} \text{ kg;} \tag{7}$$

in which i is now expressed in amperes.

Considering an alternating-current system, the fluxes φ and φ' induce respectively the electromotive forces

$$e' = 2\,\pi\,f\,\varphi'\,10^{-8} \text{ volts,} \tag{8}$$

and

$$e = 2\,\pi\,f\,\varphi\;10^{-8} \text{ volts.} \tag{9}$$

*Integrating, $W = \int_0^l F\,d\,l = \bar{F}\,l = \int_0^l i\,\frac{d\,\alpha}{d\,l}\,d\,l - \left|\int_0^i i'\,\frac{\partial\,\phi}{\partial\,i'}\,di'\right|_0^l$ ergs, which is of exactly the same form as (**63**) except for differences of notation. [Ed.

Substituting these values of the fluxes in terms of the impressed electromotive forces, we have in practical units

$$F = \frac{0.810 \times 2}{f} \left[i \frac{d\,e}{d\,l} - \frac{d}{d\,l} \left\{ \int_0^i i' \frac{\delta\, e'}{\delta\, i'}\, d\,i' \right\} \right] \text{kg.,} \quad (10)$$

and

$$F = \frac{0.810 \times 2}{f} \left[-e \frac{d\,i}{d\,l} + \frac{d}{d\,l} \left\{ \int_0^i e'\, d\,i' \right\} \right] \text{kg.} \quad (11)$$

If saturation is absent—and in most cases it can with great approximation be supposed so—the flux is proportional to the exciting current:

$$\varphi' = L\, i'; \quad (12)$$

so that

$$\int_0^i i' \frac{\delta\, \varphi'}{\delta\, i'}\, d\,i' = \int_0^i \varphi'\, d\,i'. \quad (13)$$

Adding (**6**) and (**7**) and substituting (**13**),

$$F = 0.051 \left[i \frac{d\,\varphi}{d\,l} - \varphi \frac{d\,i}{d\,l} \right] 10^{-6} \text{ kg.} \quad (14)$$

Similarly from (**10**) and (**11**),

$$F = \frac{0.810}{f} \left[i \frac{d\,e}{d\,l} - e \frac{d\,i}{d\,l} \right] \text{kg.} \quad (15)$$

(**14**) may also be written:

$$F = 0.051 \left[2\, i \frac{d\,\varphi}{d\,l} - \frac{d}{d\,l} (\varphi\, i) \right] 10^{-6} \text{ kg.;} \quad (16)$$

or

$$F = 0.051 \left[-2\, \varphi \frac{d\,i}{d\,l} + \frac{d}{d\,l} (\varphi\, i) \right] 10^{-6} \text{ kg.} \quad (17)$$

(**15**) may also be written:

$$F = \frac{0.810}{f} \left[2\, i \, \frac{d\, e}{d\, l} - \frac{d}{d\, l} (e\, i) \right] \text{kg.}; \tag{18}$$

or

$$F = \frac{0.810}{f} \left[-2\, e \, \frac{d\, i}{d\, l} + \frac{d}{d\, l} (e\, i) \right] \text{kg.} \tag{19}$$

These equations have also other forms which may be useful in special cases. Introducing reactance,

$$x = \frac{e}{i} \text{ ohms,} \tag{20}$$

we obtain the three formulas,

$$F = \frac{0.810}{f} \quad e\, i \, \frac{d}{d\, l} \left(\log_{\epsilon} \frac{x}{x_0} \right) \text{kg.,} \tag{21}$$

$$= \frac{0.810}{f} \, i^2 \, \frac{d\, x}{d\, l} \text{kg.,} \tag{22}$$

and

$$= - \frac{0.810}{f} \, e^2 \, \frac{d}{d\, l} \left(\frac{1}{x} \right) \text{kg.} \tag{23}$$

If x is constant during motion, no force is exerted

If either the current or voltage are constant,

$$F = \pm \frac{0.810}{f} \, \frac{d}{d\, l} (e\, i) \text{ kg.} \tag{24}$$

where $e\, i$ is the volt-amperes of the system. This is equivalent to equation (**54**) of the paper.

In transformers the kilovolt-amperes at short-circuit are easily determined knowing the potential difference at the terminals and the leakage. Supposing the leakage to be proportional to the distance l between magnetic centers of primary and secondary coils, then

$$\frac{d}{d\, l} (e\, i) = \frac{e\, i}{l}, \tag{25}$$

and

$$F=\frac{0.810}{f}\ \frac{e\,i}{l}\ \text{kg.} \tag{26}$$

—again the same result as in the paper.

Two parallel conductors are repelled with a force which may be determined from the above equations, considering that

$$\frac{d\,x}{d\,l}=\frac{d}{d\,l}\,(2\,\pi\,f\,L)=2\,\pi\,f\ \frac{4\times 10^{-9}}{l} \tag{27}$$

and substituting in (22),

$$F=20.4\ \frac{i^2}{l}\ 10^{-9}\ \text{kg. per cm. length} \tag{28}$$

—exactly the same result as (57) of the paper.

Much simpler indeed would it be to start from the formula

$$F=i\,\mathfrak{B}\ \text{dynes per cm.,} \tag{29}$$

in which $\mathfrak{B}$ is the flux density at the axis of the conductor. Here

$$\mathfrak{B}=\frac{4\,\pi\,i}{2\,\pi\,l}=\frac{2\,i}{l}\ \text{gausses;} \tag{30}$$

so that

$$F=\frac{2\,i^2}{l}\ \text{dynes per cm.,} \tag{31}$$

or in practical units,

$$F=20.4\ \frac{i^2}{l}.\ 10^{-9}\ \text{kg. per cm.} \tag{32}$$

as already given.

E. Jasse (by letter): I would like to call attention to an article covering the same subject which I published in "*Elektrotechnik und Maschinenbau*", *Zeitschrift des Elektrotechnischen Vereines in Wien*, *Heft* 40, 41 *u.* 42, 1910. In this article the equations 5, 6, 15*a*, 7 and 15*b* are equivalent to equations 1, 11, 16, 33 and 37 of Dr. Steinmetz's paper.

C. P. Steinmetz: Professor V. Karapetoff's historical review of the theories used in my paper is very interesting and im-

portant if complete. I never give literary references, however, for the reason which I stated in the preface of my first book:

"I have omitted altogether literary references, for the reasons that incomplete references would be worse than none, while complete references would entail the expenditure of much more time that is at my disposal, without offering sufficient compensation". (A. C. Phenomena, 1897).

As it is obvious that no paper has ever been written, which does not use the work of preceding investigators, the absence of literary references does not claim originality for every detail. When crediting priority of a conception however, the serious danger is the possibility of unfairness, by overlooking the first publication on the subject, and thereby giving credit where it does not belong. This can be guarded against, to some extent, only by such an extensive search of the literature, as is usually out of the question. Nevertheless, it is undoubtedly desirable, at least historically, to give references. This however is work, which the college professor can do very much better than the practicing engineer, as he has the time and the facilities, and I therefore express the hope, that our colleges will undertake this work of keeping the historical records of the electrical engineering science.

That the mechanical forces, with which my paper deals, are not a mere theoretical conception, but are very real, no one can gainsay who has had anything to do with transformers which have passed through a short circuit. I mean transformers of large size, built with very close regulation, from mistaken engineering notions, usually on the express requirement of customers which have forced the manufacturers against their better knowledge to design for a reactance of two per cent or even less. If such a 5,000 kw. transformer of close regulation passes through a short circuit on a system which really can maintain the voltage at the primary—a system with momentary short circuit power of millions of kilovoltamperes, as there are now quite a number in this country—the closest approach to the appearance of such a transformer is the way that I think two express trains must look after a head-on collision at high speed.

It is true that these destructive agencies have been at work more in the last years than before, but the reason is obvious—it is due to the systems on which the transformers are installed—we did not have these large power systems a few years ago, but they are increasing now more and more rapidly—which can maintain constant primary voltage with a secondary short circuit on a big transformer. In a small transformer the forces are relatively less, but they are enormous in big transformers, and what really was saving the transformer, and now still saves by far the largest majority of the transformers, is the inability of the generating system to maintain the primary voltage under secondary short circuit, and the forces go down with the square of the current, that is, with the square of the impressed voltage.

If for instance, as stated by one of the speakers, amongst many transformers tested, with five times full load current, one showed distortion—I think that is rather a condemnation of the mechanical construction—as at five times full load current the mechanical strains are only one hundredth of what they are at short circuit, with 50 times full load current, and a test with five times full load current thus is meaningless in indicating the ability of standing the short circuit stresses.

All engineering theory consists of three parts: first, to find out that a thing exists; second, to get the general theory, which is really the theory of the phenomenon as it would exist under ideal conditions, conditions which never exactly but only approximately exist in practice, for instance, parallel circular conductors carrying uniform current density, and the third part is the adoption of those general theories to the specific conditions under investigation, the calculation of the exact distance of the equivalent magnetic centers of the coils of the transformer which I referred to in the paper—the calculation of the equivalent location of conductor centers which represent the forces between parallel rectangular bus-bars—all these things are of importance in the investigation and consideration of the secondary phenomena which modify the effect of the primary or general phenomenon, which constitutes the subject matter of the paper, and I think it is very gratifying to see that the discussion has already extended to these secondary questions by giving us a very explicit study of the secondary actions which have to be considered in applying the general equation to the specific cases of rectangular conductors, of transformer coils, etc.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

THE REGULATION OF DISTRIBUTING TRANSFORMERS

BY C. E. ALLEN

With the many improvements made in distributing transformers during the past few years, especially since the advent of the so-called silicon steels (by the use of which the iron loss of transformers has been greatly reduced), the tendency has been to lay particular stress upon the iron loss characteristics, with the result that other electrical characteristics, such as exciting current and regulation, have scarcely received the attention that their importance deserves. In reviewing the published claims made by the various manufacturers, we find that the two last named characteristics have not been improved in the same proportion as the iron loss. While the author recognizes that both a low exciting current and good regulation are of great importance, this paper will be confined to a discussion of regulation; its relation to the other characteristics of distributing transformers and its effect on the economical operation of the modern central station.

The regulation of a transformer operating on a non-inductive load is defined by the A. I. E. E. as " the ratio of the rise of secondary terminal voltage from rated non-inductive load to no-load (at constant-primary impressed terminal voltage) to the secondary terminal voltage at rated load." The value of the regulation of the average distributing transformer at present on the market varies from 1 per cent to $3\frac{1}{2}$ per cent, and when operated on power factors as low as 60 per cent, the regulation in some instances is as high as 4 per cent.

The published regulation of the transformers of different

manufacturers varies, not only due to the different designs, but also to the various methods used in making the calculations. It is customary to measure the resistance of the windings by the "fall of potential" method and the impedance of the windings by the short-circuit test, and to obtain the regulation from this data by substitution in some arbitrary formula.

The following are some of the more important formulas in use: The per cent regulation at 100 per cent power factor

$$= I\,R + \frac{(I\,X)^2}{200} \tag{1}$$

Neglecting the last term

$$= I\,R \tag{2}$$

At any power factor the per cent regulation

$$= I\,R\cos\phi + I\,X\sin\phi + \frac{(I\,X\cos\phi - I\,R\sin\phi)^2}{200} \tag{3}$$

Neglecting the last term

$$= I\,R\cos\phi + I\,X\sin\phi \tag{4}$$

At any power factor the per cent regulation

$$= 100\,\sqrt{1 + c^2 + d^2 + 2\,c\cos\phi + 2\,d\sin\phi} - 1 \tag{5}$$

At 100 per cent power factor the per cent regulation

$$= I\,R + \frac{(I\,X)^2 + 2\,I\,X\,m}{200} \tag{6}$$

At 100 per cent power factor the per cent regulation is calculated from the following formula, which gives the value of the no-load secondary terminal e.m.f.:

$$E = \sqrt{(100 + I\,R\cos\phi + I\,X\,W)^2 + (I\,X)^2} \tag{7}$$

At any other power factor

$$E = \sqrt{(100 + I\,R\cos\phi + I\,X\,W)^2 + (I\,X\cos\phi - I\,R\,W)^2} \tag{8}$$

The symbols used in the above formulas are,

$I\,R$ = Total resistance drop in the transformer expressed in per cent of rated voltage.

$I\,X$ = Reactive drop similarly expressed.

E = No-load secondary terminal e.m.f.

Φ = Angle of lag of secondary current behind secondary voltage.

Cos ϕ = power factor of load.

W = (wattless component of load plus the magnetizing current), expressed as a decimal fraction of full load current.

m = Per cent magnetizing current.

c = $I\,R \div 100$.

d = $I\,X \div 100$.

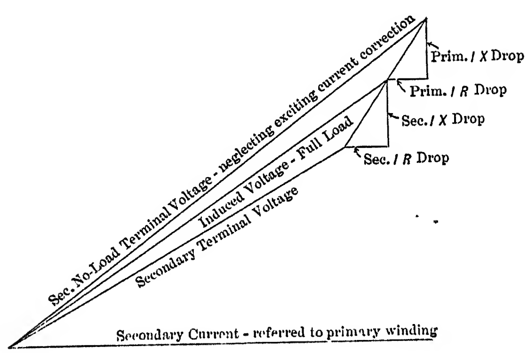


FIG. 1

Assuming a transformer having a resistance drop equal to 1.5 per cent and a reactance drop equal to 2 per cent and a magnetizing current equal to 5 per cent, the following table gives the regulation at different power factors calculated by substitution in the above formulas:

PER CENT REGULATION

Formula	Power factor 100 per cent	Power factor 90 per cent	Power factor 80 per cent	Power factor 70 per cent	Power factor 60 per cent	Power factor 50 per cent
1 and 3	1.52	2.23	2.40	2.48	2.50	2.48
2 and 4	1.50	2.22	2.40	2.48	2.50	2.48
5	1.50	2.22	2.40	2.48	2.50	2.48
6	1.62	—	—	—	—	—
7 and 8	1.62	2.32	2.5	2.58	2.6	2.58

From the foregoing equations, it is obvious that there are few characteristics of a transformer that do not, directly or indirectly, influence the regulation. It is the belief of the author that formulas 1 to 4 give the most accurate results. The fact that a variation still exists in the methods of figuring the regulation used by the various manufacturers, indicates that the regulation has not been given the same consideration as other characteristics. Otherwise it appears that some standard method would have been adopted.

From the very definition of regulation as well as the fact that the exciting current is present in the transformer at no-load and full load, and therefore has practically the same in-

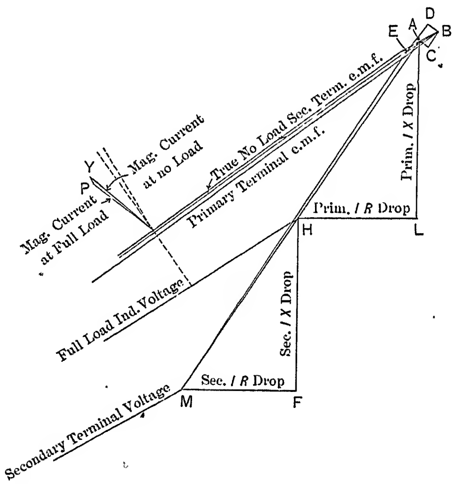


FIG. 2

fluence at both loads, it follows that the regulation obtained by either formula (1 to 4) approximates more closely the true value. This is illustrated in Figs. 1 and 2. From Fig. 1 formulas 1 to 4 may be deduced. Fig. 2 substantiates the fact that formulas 1 and 3 are more accurate than those formulas wherein the exciting current is incorporated.

From Fig. 2 it is seen that as long as the exciting current remains constant in magnitude and in phase relation to the induced e.m.f., the presence of exciting current does not affect the regulation one way or the other, but that the decrease in, and phase displacement of, the exciting current from no-load to full load has a tendency to improve the regulation.

The diminution of the exciting current is due to the fact that a large proportion of the primary impressed e.m.f. is consumed in forcing the full load current through the winding and therefore the induced e.m.f. is reduced, with resulting decrease in flux density in the iron and a corresponding decrease in exciting current. The phase displacement is due to the fact that as the exciting current is reduced in value, the iron loss component of the exciting current is reduced by a smaller percentage than the magnetizing component; this is true for values of the induction commonly used in distributing transformers. At fairly low inductions, however, the reverse of the above is true.

The vectorial change in the exciting current is shown in Fig. 2 by the line *Y P*, and the vectorial increase in the secondary induced e.m.f. is shown by *E A*.

No doubt the reason that led to incorrectly incorporating the

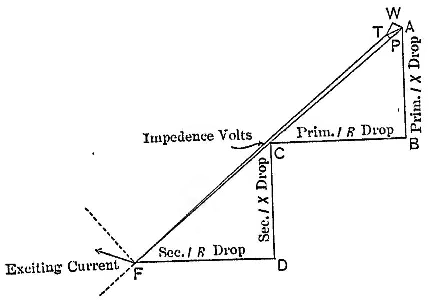


FIG. 3

exciting current in some of the foregoing formulas was due to its influence on the power factor in the primary windings of the transformer. A change in the power factor of the load does affect the regulation, but inasmuch as the change referred to is on the primary winding only, it does not affect the ratio of the change from no load to full load in the voltage across the terminals of the secondary winding to the full load voltage, and this agrees with the definition of regulation.

The impedance is ordinarily measured by short circuiting the secondary and putting full load current into the primary of the transformer. A small component of this current must necessarily be magnetizing current so that if full load current is flowing in the primary, the secondary current is slightly less than full load. In Fig. 3 the measured impedance is equal to *F T*, the true impedance would equal *F A*. This is greater than the

measured impedance by PA. The error introduced is, however, quite small. Furthermore, the difference between the actual voltage drop from no-load to full load, with flux and magnetizing current constant, and that calculated from the short circuit impedance, as shown in Fig. 3, is practically compensated for by the reduction of the voltage drop, due to the fact, shown in Fig. 2, that the magnetizing current is less at full load than at no-load. Therefore, the regulation resulting from formulas 1 and 3 is as correct as it is possible to obtain.

In considering the influence on regulation of the transformer characteristics, which have been claimed to be most important, it is not surprising that the regulation of modern distributing transformers is not as consistent as its importance warrants.

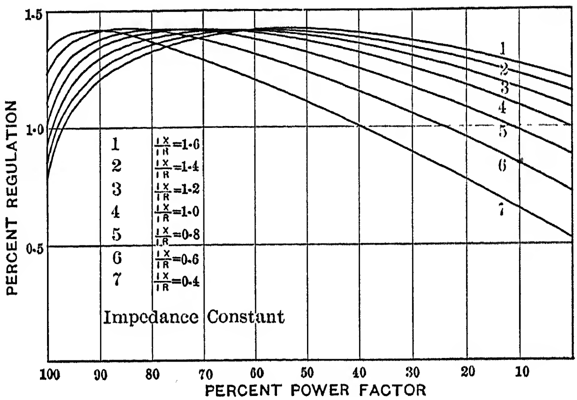


FIG. 4

This is probably due to the fact that the iron and copper losses were pre-determined and the regulation was made as low as possible consistent with these limitations. Inasmuch as the copper loss and the reactive drops are controlled directly by the pre-determined characteristics, Figs. 4 and 5 are given to show the variations in the regulation with certain given values of the IX and IR drop. Fig. 4 shows the variation in the regulation with the impedance constant as the power factor changes, and from this it will be seen that where circuits have a power factor greater than 70 per cent, the ratio of $\frac{IX}{IR}$ should be greater than one to obtain the best regulation for a constant impedance.

On the other hand, if the transformers are to be operated at power factors less than 70 per cent, then the ratio of $\frac{I X}{I R}$ should in general be less than one. In Fig. 5 is shown the variation in the regulation with the resistance constant and the reactance variable. From this it is seen that as far as regulation is concerned the best transformer for all power factors is one with the ratio of $\frac{I X}{I R}$ as small as possible. Fig. 6 shows that with the reactance constant and copper loss drop variable, the best transformer for all power factors, from the standpoint of regula-

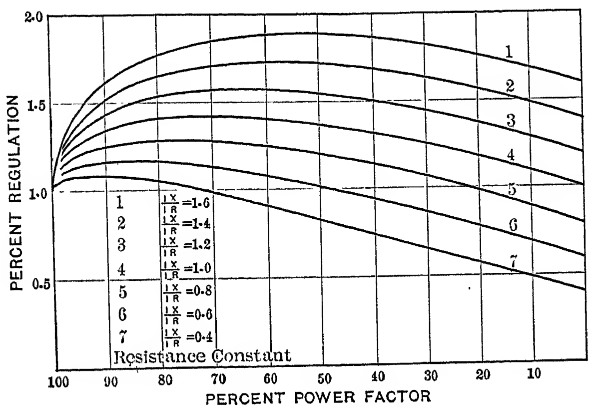


FIG. 5

tion, is one where the ratio of $\frac{I X}{I R}$ is as great as possible. Figs. 5 and 6 are of value only in showing the variation in the regulation for certain changes in other characteristics and how regulation of a given value may be maintained by changing the construction of the windings in a transformer having the same general dimensions.

It is usually impractical to obtain transformers with the best regulation unless some other characteristic is sacrificed. Therefore, each characteristic in a well balanced design should be given due consideration, and one made equally as good as another, depending upon its relative importance to the economy of operation of the average central station.

If, at the present time, the manufacturers were called upon to improve the regulation, this could be accomplished only at the sacrifice of other characteristics of the transformer, or an increase in the active material of the transformer, or by improvements in material.

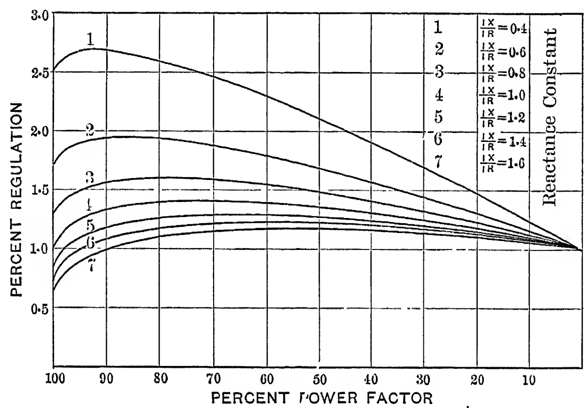


FIG. 6

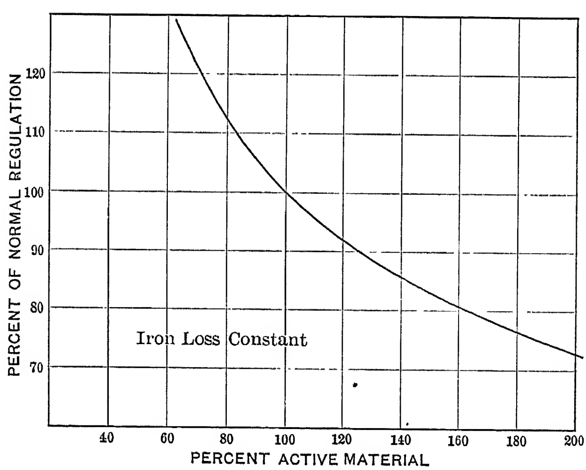


FIG. 7

In Fig. 7 it will be seen that by maintaining a constant iron loss, any reduction in the regulation would mean a considerable increase in active material necessary. It must be remembered that with the condition as shown in Fig. 7, the copper loss would

also be reduced in the same ratio as the regulation. From Fig. 8 it will be seen that with the active material constant, any further reduction in the regulation must be made at the sacrifice of the iron loss, or reversing this statement, it may be said with present quality of materials that any further reduction in the iron loss would be at the sacrifice of the regulation.

Consider the relative value of the regulation as compared with other characteristics in the economical operation of a central station; taking for example one where the cost of generating is one cent per kilowatt-hour, and the energy is sold at seven cents per kilowatt-hour, this being assumed as a proportionate average of the lighting and power rates. The average full load operation

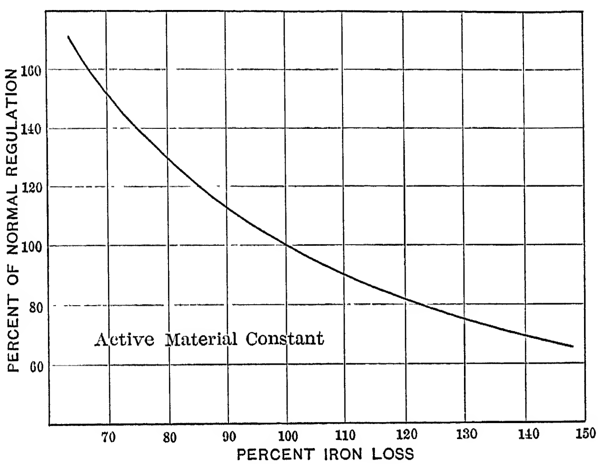


FIG. 8

per day to make the value of the regulation equal that of the iron loss would be only four hours, inasmuch as the regulation would be evaluated at six cents per kilowatt-hour. These figures are based on a power factor of 100 per cent which is, of course, higher than the average central station power factor. Considering the improvement in the lighting service obtained by the consumer when transformers of better regulation are used, it would appear that the value of the regulation is greater than that of the iron loss when the transformer is operating at full load, or its equivalent, for more than four hours per day. There are certain local conditions in every central station that tend to modify the foregoing results, such as free lamp renewals, the price of power, the cost of generating, etc.

While it is true that most of the central stations are adopting induction feeder regulators to compensate for the line regulation, they cannot be made to compensate for transformer regulation inasmuch as there are necessarily a number of transformers of different capacity on the same feeder which do not have the same regulation and which furthermore are not equally loaded at the same time.

To obtain a good regulation on modern transformers, when the values of other characteristics have been predetermined, resort has been made to many different methods. Fig. 9 shows the

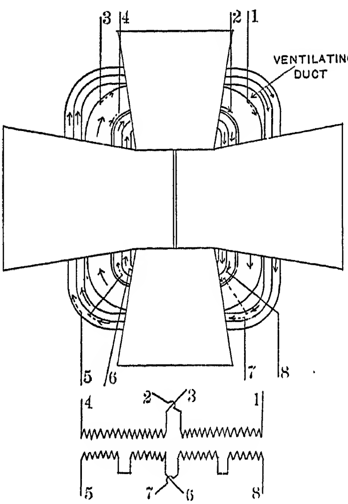


FIG. 9.—Relative arrangement of windings of small distributing transformers

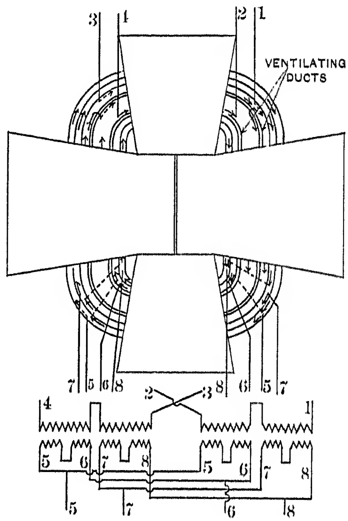


FIG. 10.—Relative arrangement of windings of large distributing transformers

internal connections of the coils on the smaller sizes of the distributed shell type transformers, while Fig. 10 shows the interconnection of the coils on the distributing transformers of larger capacity where continuous oil ducts have been introduced to provide for the cooling. It may be noted in Fig. 10 that one of the oil ducts is placed between two sections of the high tension winding. This serves two functions, one to cool the primary, which, having a low space factor, might otherwise run excessively hot and the other to provide better regulation than would be

obtained if the duct was placed between the low tension and high tension coils, thereby increasing the reactance. Fig. 11 shows the shell type transformer with "pan-cake" coils and it will be noted that a large number of coils are necessary in that they are interlaced, for the purpose of reducing the reactance and thereby securing a low regulation. The core type of transformer is shown in Fig. 12. It will be noted that a low regulation is obtained by long cylindrical coils without any interlacing of same.

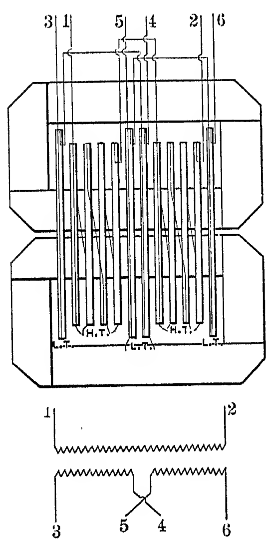


FIG. 11.—Relative arrangement of windings on shell type distributing transformer

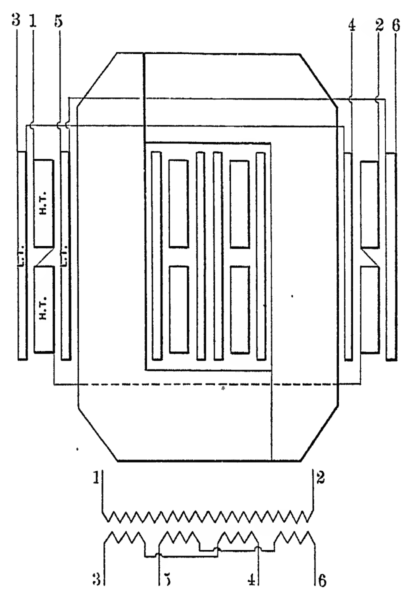


FIG. 12.—Relative arrangement of windings on core type distributing transformer

The methods of inter-connection and interlacing, as illustrated, enables as good a regulation to be obtained with the three-wire secondary operation as with the two wire service. In fact, the methods shown in these illustrations have made it possible for the manufacturers to guarantee a regulation on either side of the three wire system, when one side is loaded, and the other unloaded, to be as good as the regulation of the two wire system.

With reference again to Figs. 9 and 10, which show the latest construction of the distributed shell type transformers, it is interesting to note the method used in interlacing and connecting these windings in order to obtain the very lowest possible results for given conditions. This exemplifies the care that has been taken to obtain the very best regulation in modern transformers.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

THE TEMPERATURE GRADIENT IN OIL IMMERSED TRANSFORMERS

BY JAMES MURRAY WEED

High temperatures are objectionable in transformers for several reasons. The first of these is their effect on the insulating materials, which are subject to gradual deterioration at temperatures of about 100 deg. cent. and to rapid destruction at temperatures greatly in excess of that figure. A second reason, which is not nearly so important, but nevertheless a valid objection, is their effect upon copper loss, which increases about 10 per cent with an increase of 25 deg. cent. in the temperature. Another reason, with oil-insulated transformers, lies in the effect of high temperatures upon some oils, in the deposition of solid hydrocarbons. This forms a coating on the surface of the coils and core, and clogs the ducts, thus increasing the temperature in the windings. The temperature at which this process begins depends upon the character of the oil used. A fourth objection to high temperatures existed formerly in the aging effect of temperatures exceeding about 70 deg. cent. upon the iron used in the core, thus increasing the core loss. This objection does not exist in connection with the present improved steel, which is non-aging.

With respect to the effect of high temperature upon the insulating materials, it is the point in the windings where the temperature is maximum that is important. This temperature may be considerably higher than the average temperature, which is measured when the transformer is tested. And again, with respect to the deposition of solid hydrocarbons, this depends upon the maximum temperature to which the oil is subjected at the immediate surface of contact with the coils or core, rather

than upon the temperature which is measured at the top of the oil.

A knowledge of the distribution of temperature throughout the transformer, and of the various things which affect this distribution, is important from the standpoint of those who use transformers, to enable them, for instance, to judge from the average temperature rise of the transformer windings, or better still, from the temperature of the oil at the top of the transformer, what may be the maximum temperature rise in the windings. Such a knowledge is important from the standpoint of the designer, to enable him to adopt those conditions which are most favorable to cooling, avoiding an unequal distribution of temperature, and obtaining the minimum temperature rise for a transformer of given cost and rating. Stating the case differently, it will enable him to build a transformer of a given rating, and with given temperature rise, at the minimum cost.

The general subject of temperature rise in transformers has received much attention, which may be said to fall in three classes. The first class may be termed the statistical method of investigation. By this method the temperature rise, as determined by test, is recorded without particular reference to details of design. In effect, transformers are looked upon as reservoirs of heat, all the resistance to its escape existing in two uniformly distributed layers, the one being at the surface of the transformer, and the other at the surface of the tank. From the results of the test, rules are laid down for the designer, based upon the watts per square inch at each of these surfaces. Owing, however, to variations in design which affect the temperature rise, but are not taken into account, these rules are not always safe. It thus happens that occasionally transformers are built which exceed their temperature guarantees. On the other hand, many transformers are built which operate cooler than is required, and since temperature rise is what really limits the capacity of a transformer, the actual capacity is usually more or less than that which was intended. The knowledge of temperature rise gained in this way applies reasonably well to standard types, but may be of little value for estimating the performance of a transformer which is a radical departure from standard practice, and is of no use for determining what will be the most economical design when considering new types. Nor does it at all tell us what are the maximum temperatures reached in the windings of a given transformer.

In the second class of investigation, much work has been done in testing different methods of cooling, under specific conditions, and comparing results from definite changes in these conditions. Much valuable information has been gained in this way as to the relative merits of the definite combinations of conditions tested. Such tests are made upon complete transformers, and the number of combinations of conditions tested is therefore necessarily limited to those existing in available transformers. The significance of such tests is often lost from the fact that several conditions existing in a given transformer may be different from those existing in any other transformer with which it is compared. If such a system of investigation were continued indefinitely, it is possible that ultimately the most economical design from the standpoint of cooling might be arrived at, but it would be at very great cost in " development work "—testing new ideas, making new designs, new standard lines of parts, etc., and this method also would never tell what is the maximum temperature in the windings.

A third class of investigation is that which undertakes, by a study of the laws of cooling, to formulate a correct theory applicable to the general case, which will indicate once for all that combination of conditions which is most favorable to cooling, and enable one to say with considerable accuracy not only what will be the average temperature rise in any given case, but also what will be the maximum rise. Some very praiseworthy efforts have been made in this direction, but the field to be covered is large, and in order to attain that degree of success which is desirable such a study must go hand in hand with experimental work. Tests on complete transformers will not answer for this purpose, but experiments must be specifically designed to answer the questions involved, separating as much as possible the feature under consideration from all other influences. It is necessary to make a separate study of each step in the temperature gradient, determining first what conditions affect it, considered alone, and then how it is related to all the other steps. Though a large amount of experimental work and study will be involved in such an investigation, nevertheless it will be the cheapest and most satisfactory method for obtaining the desired information. The investigation may be limited, moreover, to those conditions and combinations of conditions which are practicable of application in transformer construction, when all other requirements than those of temperature rise are con-

sidered, and to those which it is thought may conduce to economy.

This paper relates to the third method of investigation described above, and though it will be impossible, at this time, to give the subject complete treatment, what follows is an effort to properly outline it, as a basis for discussion and a foundation for future work.

In passing from the hottest part of the transformer coils, or core, to the final cooling medium, for an oil-immersed transformer, the temperature gradient may be considered in seven parts, as follows:

1. From the hottest part of the coil to its surface, within the insulating covering, if the coil is covered.
2. Through the insulating covering on the surface of the coil to its outside surface.
3. From the surface of the solid insulating covering, or coil, into the adjacent oil.
4. Through the oil from a point adjacent to the coil, to a point adjacent to the tank for a self-cooling transformer, or to a point adjacent to the cooling coil for a water-cooled transformer.
5. From the oil to the metal of the tank or the cooling coil.
6. Through the walls of the tank or the cooling coil.
7. From the external surface of the tank to surrounding air, or from the inner surface of the cooling coil into the water.

These different steps cannot, however, be looked upon as definite, since the range of temperature occurring in any given step may have a wide variation for different parts of the same transformer. This condition, together with the difficulty in tracing the paths of heat discharge, and our lack of complete knowledge of nature's method of transferring heat, complicate the whole problem.

The difficulty of this problem may be better understood if we compare it with the related one of the distribution of electric potential throughout the insulating materials of the transformer. The electrostatic flux and potential in the one case are analogous to the heat flow and the temperature respectively in the other. In the problem of the distribution of potential, the potential of every portion of the windings is arbitrarily fixed. In the problem of the distribution of temperature the temperature of the windings is not fixed but must be determined. In this case the total heat flow is fixed. The difficulties of the potential problem, owing to irregular distribution of the electrostatic flux, is pretty

generally understood. In the thermal problem we find similar difficulties, owing to the irregular distribution of the flow of heat. We have here, also, the added difficulty of the disturbing effect of convection currents and eddies, in the oil, and in the air, or the water, which not only modify the distribution of any given flow of heat, but also change the distribution when the rate of heat discharge changes. We have also another complication due to the fact that the flow of heat does not originate at the surface of the coil, but throughout its substance. This distributed origin of the heat, together with the distribution of thermal resistance found within the coil, affect the distribution of heat flow on the surface of the coil, and so affect the temperature distribution outside of the coil as well as inside.

It will be understood then that with this problem, even more than with the one of potential distribution, any theoretical treatment must be based upon simplifying assumptions, which are more or less at variance with the actual conditions of any particular case. For certain ideal sets of conditions these assumptions will apply approximately. Here the subject is susceptible of rational treatment, and the only experimental work required is that which is necessary for checking the theory and for determining the constants involved. In general, however, good judgment must be used in applying the rational treatment, and this can be obtained only by that close relationship between theoretical treatment and experimental work indicated above. On the one hand, theory will act as a guide in outlining the experiments, and on the other hand judgment in applying the theory, and assistance in modifying it to more nearly fit the conditions, will be obtained from the tests.

Within the range of the temperature gradient of which the various steps are outlined above, radiation, conduction and convection are all involved. It is necessary therefore to give distinct consideration to these different means by which heat is transferred.

Though much of the best talent for scientific investigation that the world has produced has been expended in the investigation of this subject, the difficulties are so great that the laws of cooling are not yet thoroughly understood. The law of direct proportionality between heat flow and temperature difference holds in the case of conduction only, and even here it is complicated by the fact that changes in temperature affect the thermal resistance of materials as well as their electrical re-

sistance. This effect may probably be ignored however for the temperature ranges involved in transformer cooling.

The transfer of heat by conduction occurs alone in the 1st, 2nd, and 6th steps of the temperature gradient as outlined above, and in conjunction with convection in the 3rd, 5th and 7th. Where conduction operates alone, the temperature drop in the direction of the heat flow is expressed in terms of the product of the density of the heat stream, the specific thermal resistance of the material and the length of the path considered. The units used in this paper are, respectively, watts per square inch, degrees cent. per mil and per watt per square inch, and mils.

Radiation appears in our problem in the transfer of heat from the tank to the walls of the room, or surrounding objects, and also to some extent from the coils and core to the tank, since the diathermacy of oil is probably somewhere between 25 and 30 per cent. In the former case it acts, so to speak, as a shunt to step 7, and in the latter as a shunt to steps 3, 4 and 5, of the temperature gradient.

For radiation, according to the Stefan-Boltzmann law, the relation between temperatures and heat emitted is expressed by the equation:

$$R = K\,(T_1^4 - T_2^4)$$

where R is the rate of heat emission, T_1 and T_2 are the absolute temperatures of the cooling body and its surrounding objects respectively, and K is a constant, the value of which depends upon the units used. If R is expressed in watts per square inch and T_1 and T_2 in degrees cent., the value of K is, for the theoretical black surface, 3.425×10^{-11}.

This law applies accurately only to the black surface, and would lead to large errors if applied to surfaces which radiate poorly, over wide ranges of temperatures. It will probably apply with sufficient accuracy however, over the ranges of temperature in which we are interested, if we have the proper values for K to apply to the different kinds of surface. By substitution in our formula of the results from Peclet's experiments for the heat radiated from the surface at 100 deg. cent. to its surroundings at 0 deg. cent., we obtain the following values:

Ordinary sheet iron	2.275×10^{-11}
Sheet iron polished	0.189×10^{-11}
New cast iron	2.61×10^{-11}
Rusted iron	2.75×10^{-11}

Terne plate	0.535×10^{-11}
Lamp black	3.29×10^{-11}
Full radiation	3.425×10^{-11}

In considering the effect of paint, although we have no very definite information, we may draw some general conclusions from the experiments of Melloni and others on comparative radiating power at 100 deg. cent., recognizing the fact that these figures are only approximate. The following figures are found in text books on "Heat."

Lamp black	100
White lead	100
Ivory, jet, marble	93 to 98
Glass	90
Indian ink	85
Steel	17
Polished brass	7
Polished silver	3

For absorptive power the following figures are given:

	Oil lamp	Incandescent platinum	Copper 400 deg. cent.	Hot water Cb. 100 deg cent.
Lamp black	100	100	100	100
Indian ink	96	95	87	85
White lead	53	56	89	100
Shellac	48	47	70	72
Metallic surface	14	13.5	13	13

These figures indicate that the color of a pigment paint makes little difference at ordinary temperatures, although at high temperatures the lamp black radiation would be much greater than that, for instance, of white lead. With a metallic paint, however, the radiation is considerably reduced.

The importance of radiation in the cooling of transformers, or electrical apparatus in general, is often overlooked, as there seems to be a popular impression that radiation plays a small part as compared with convection. Take the case of an ordinary boiler tank, with plain surface, the total heat discharged by both radiation and convection, with a rise of 40 deg. cent. in the top of the oil, is ordinarily about 0.25 watt per sq. in. (0.04 watt per sq. cm.). The value of K for the boiler iron tank, painted, is probably not less than 3×10^{-11}. If we assume the

temperature of the surrounding objects to be 25 deg. cent., and that the average temperature of the surface of the tank is 7 deg. cent. lower than the top oil, the heat lost by radiation is about:

$$R = 3\times10^{-11}\,(331^4 - 298^4)$$

$$= 0.1235 \text{ watts per sq. in. } (0.0191 \text{ watts per sq. cm.})$$

This is about 50 per cent of the total heat emitted. This proportion does not hold, however for the corrugated tank, or tank with external radiating tubes. The increased cooling with a corrugated surface is due mainly to the increase in convected heat. The radiation is not increased at all except in so far as the external dimensions of the tank are increased; since the radiation in any direction is proportional to the projection of the tank upon a plane at right angles to that direction.

With a constant room temperature of 25 deg. cent., the effect

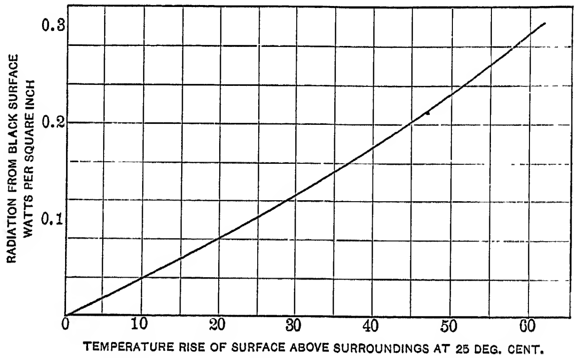


FIG. 1

of temperature rise upon radiation, as expressed by the Stefan-Boltzmann law, is represented by the curve in Fig. 1, while the radiation for the temperature rise of 40 deg. cent., for different room temperatures, is shown in Fig. 2.

The action of radiation is somewhat complicated by the fact that, though dry air is perfectly diathermous, water vapor is not, so that a varying portion of the radiated heat is absorbed in the immediate neighborhood of the tank, depending in amount upon the density of the water vapor. Although this heat has been actually discharged from the tank, by raising the temperature of the air in the immediate neighborhood of the tank, it affects the amount of heat which will be discharged by convection. A similar action takes place in the oil in the immediate neighborhood of the coils and core. The shunting action of

radiation referred to above is thus somewhat modified, since a part of the heat radiated from the coils and core shunts step 3 only.

Convection plays a very important part in the cooling of transformers, by carrying the heat away from the tank, and by transporting it from the surfaces of coils and core to the tank, or to the cooling coil. Without convection the process of cooling, apart from radiation, would consist in the conduction of heat through the enormous thermal resistance of the mass of oil in the tank, and again, of the air outside of the tank.

The third step in our temperature gradient may be looked upon as one of conduction through a thin layer of oil, the thickness of this equivalent layer depending upon the velocity of the oil

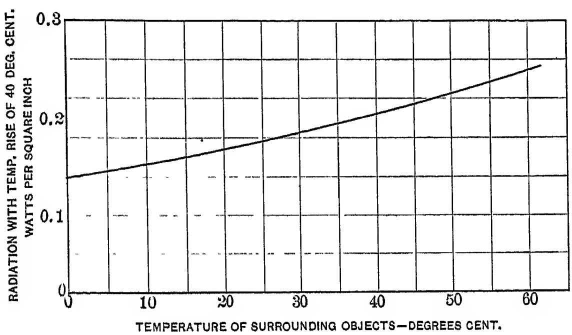


FIG. 2

flow over the surface. This effect of velocity upon the thickness of the conducting layer may be the same, whether it be artificially produced, as in forced circulation, or whether it be due to the unaided action of convection. With artificial circulation and a given rate of flow the thermal resistance of this step is constant, and the temperature drop through the conduction layer is directly proportional to the density of the heat stream in watts per square inch. When, however, the circulation is that due to convection alone, an increase in the amount of heat discharged will result in an increased velocity, and hence in a reduction of the equivalent thickness of the layer of conducting oil. The thermal resistance is thus reduced with increased heat discharge, so that the temperature drop does not increase in direct proportion to the watts per square inch, but is smaller in proportion as the watts increase.

The action at the inner surface of the tank, or the outer surface of the cooling coils, step 5, is very similar to that of step 3,

the difference being that the heat flow is from the liquid to the solid instead of from the solid to the liquid.

Now convection alone is concerned in the bodily transportation of heat, in step 4, from the conductive layer on the coils or core to that on the cooling coils or tank. It is, moreover, as a physical fact, hopelessly involved with conduction in the third and fifth steps, and also in the seventh, in a manner which may be pictured in a general way by the imagination, but cannot be adequately expressed mathematically. Although it has been attempted to give this subject rational treatment, probably any such treatment must be based upon simplifying assumptions which are so far from the true conditions as to be of little value, and the subject can be most properly dealt with experimentally, adopting empirical formulæ when they are found to fit, but carefully restricting them to those conditions for which they are devised.

To take up the various steps in our temperature gradient more in detail, we will start from the hottest part of the coil, and consider the steps in order.

If the cooling surfaces of the coil are parallel with the layers, the heat from the interior portion must pass from layer to layer, and there will be a temperature rise toward the interior of the coil due to the thermal resistance of the layer insulation.

Let ρ = the thermal resistance per mil in thickness of one square inch of the layer insulation expressed in deg. cent. with one watt per square inch flowing.

Let i = the thickness of insulation between layers in mils.

Let q = the watts generated in one square inch of each layer.

Let n = the number of layers of conductors from the hottest part of the coil to its surface, whence

$n - 1$ = the number of layers of insulation, if there is no layer of insulation over the outside layer.

Now the temperature rise of the second layer from the outside above the temperature of the first is $q\,i\,\rho\,(n - 1)$, that of the third above the second, $q\,i\,\rho\,(n - 2)$ etc., to the hottest layer, whose temperature rise above the one next to it is $q\,i\,\rho$. The temperature rise of the hottest layer above the temperature of the outside one is, therefore,

$$t_{max} = q\,i\,\rho\,\frac{n^2 - n}{2}$$

$$= q\,i\,\rho\,(n - 1)\,\frac{n}{2}$$

If the coil cools equally in both directions, or all in one direction, the average temperature rise of the coil above the temperature of the surface layer will be

$$t_{av} = q\, i\, \rho\, (n - 1)\, \frac{2\, n - 1}{6}$$

If n is large, this is practically

$$t_{av} = q\, i\, \rho\, (n - 1)\, \frac{n}{3}$$

so that

$$t_{av} = \tfrac{2}{3}\, t_{max.}$$

When n is small

$$t_{av} > \tfrac{2}{3}\, t_{max.}$$

The values of ρ for ordinary layer insulating materials is about 0.3. That is, a temperature, difference of about 0.3 deg. cent. for each mil in thickness is required to force one watt per square inch through a layer of the material.

The value of q at 25 deg. cent. is

$$q = 0.6935 \times 10^{-6}\, c\, s\, D^2$$

where c = the thickness of the layer of conductors s = the space factor in the layer and D = the current density in amperes per square inch.

At 75 deg. cent. this value would be

$$q = 0.825 \times 10^{-6}\, c\, s\, D^2$$

If we substitute the value of q in the formulæ for temperature rise, inspection shows that the rise is proportional to the square of the current density, and to the thickness of the layer of conductors, and that it is approximately proportional to the square of the number of layers where the number of layers is large, being greater in proportion for smaller numbers of layers.

If we consider the effect of changing the size of the conductor for a given transformer without changing its shape, or the number of layers, we have:

$$c = \text{Const.} \times \frac{1}{D^{\frac{1}{2}}}$$

whence the temperature rise is proportional to the $\frac{3}{2}$ power of the current density. If the thickness of the conductor remains constant, its width in the layer being varied, the temperature rise is proportional to the square of the current density, since c does not change. If the width of the conductor remains constant, we have

$$c = \text{Const.} \times \frac{1}{D}$$

so that the temperature rise is directly proportional to the current density.

If the cooling surfaces are at right angles to the layers, the heat is discharged from turn to turn in the layer instead of from layer to layer. Since the turn insulation is ordinarily much thinner than the layer insulation, the temperature rise within the coil, for given thickness and current density, will be much smaller in this case. It may be calculated in the same manner, but if the turn insulation be of cotton covering, the value of ρ in this case will be smaller since the thermal resistance of the impregnated cotton is smaller than that of the materials ordinarily used for layer insulation.

The temperature rise of the outer layer of the coil above the temperature of the outer surface of the insulating covering depends upon the same principles as those controlling the temperature rise within the coil. This temperature rise is

$$\tau = q\, i\, \rho\, n$$

Comparing this temperature rise through the insulating covering with the average temperature rise within the coil, for a coil with a large number of layers, it is seen that with an insulating covering of the same thickness as the layer insulation, and with the same specific thermal resistance, this rise is the $\frac{3}{n-1}$ th part of the average interior rise. Thus the temperature rise through the covering is three times as great as the average interior temperature rise divided by the number of layers of insulation, or the insulating covering needs only to be $\frac{n-1}{3}$ times as thick as the

layer insulation to make the temperature drop from the outside layer through the insulating covering as great as the average rise of the coil above the temperature of the outside layer.

The above discussion is based upon the assumption that the total heat flow is perpendicular to the cooling surface considered. This condition is approximately fulfilled in the case of a long cylindrical coil mounted vertically, the turns of the conductor being in a horizontal plane, although in this case the ends of the coil will be somewhat cooler, owing to the heat which passes out at the ends. Also, if the temperature of the oil adjacent to the top portion of the coil is much higher than at the bottom, there will be a tendency to transmit heat downward in the coil. The heat so transmitted will be small, however, since the thermal resistance is high as compared with the temperature difference in this direction. The most important result will be that the temperature of the top portion of the coil will be almost as much higher than the temperature of adjacent oil as that of the bottom portion is above the oil adjacent to it. This, of course, assumes that the equivalent thermal resistance from the coil to the oil is practically uniform throughout the length of the duct. The total average temperature of the coil is therefore related by the equations given, with sufficient approximation, not to the surface temperature at the bottom of the coil, but to a temperature which is average for the entire surface, which may be considerably higher than that at the bottom; also, the maximum temperature at the top of the coil may be considerably higher than the maximum calculated by the formula from this average surface temperature, and should be calculated from the surface temperature near the top of the coil.

We come now to the most difficult part of the whole problem, with natural oil circulation, namely, the distribution of temperature through the oil, from the solid surface of the coil to the surface of the tank, or cooling coil. The dependence of the equivalent thermal resistance from the surface of the coil to adjacent oil upon the velocity of the oil has already been pointed out. For a given velocity this resistance is constant, the temperature drop from coil to oil being directly proportional to the watts per square inch discharged from the coil. This is true also of the temperature rise in the oil as it passes through the duct. Thus, with forced circulation, returning the oil to the ducts at a definite temperature, the whole problem is simplified, the only lacking element being a definite knowledge of the relation

between the equivalent thermal resistance at the surface of the coil, and the velocity of the oil.

With natural circulation the oil flow is caused by the difference in temperature between the average temperature of the oil inside the duct and that of the outside oil, between the levels of entrance to and exit from the duct. The head producing this circulation is

$$h = \gamma L (\theta_{av} - \theta_{av}')$$

where γ is the coefficient of expansion of oil L is the length of the duct and θ_{av} and θ_{av}' are the average temperatures inside the duct and outside the duct respectively, these temperatures being measured from the temperature at the bottom of the duct. This head is consumed almost entirely by friction, since the velocity head is negligibly small. If the friction of oil is directly proportional to the velocity, and inversely proportional to the length of the duct, we may write

$$V = \frac{\text{const.} \times \gamma L (\theta_{av} - \theta_{av}')}{L}$$

$$= \text{const.} \times \gamma (\theta_{av} - \theta_{av}')$$

If we call the specific heat of oil 0.434, and its density 0.875, the temperature rise of the oil during its passage through the duct, where heat is discharged into one side of the duct only, is

$$\theta_{max} = \frac{n\, q\, L}{26\, V\, d}$$

where d is the thickness of the duct. If heat is discharged into both sides of the duct this will be

$$\theta_{max} = \frac{2\, n\, q\, L}{26\, V\, d} = \frac{n\, q\, L}{13\, V\, d}$$

Substituting for V, this becomes

$$\theta_{max} = \frac{n\, q\, L}{13 \times \text{const.} \times \gamma\, (\theta_{av} - \theta_{av}')d}$$

For the cylindrical coil which turns in a horizontal plane,

$$\theta_{av} = \tfrac{1}{2}\,\theta_{max}.$$

If we have a diaphragm separating the oil in contact with the tank from that in contact with the outside coils of the transformer, the temperature of the oil adjacent to the tank, plotted up the side of the tank, will be a straight line, so that

$$\theta_{av}' = \tfrac{1}{2}\,\theta_{max}'.$$

Now in order that circulation may occur θ_{av}', must be less than θ_{av}, whence θ_{max}' must be less than θ_{max}. This is accomplished by the mixing of the hot oil leaving the duct with other oil which has been cooled by contact with the tank. We find that this mixing results in a practically uniform temperature of oil from the top of the transformer to the top of the oil, which is practically the temperature θ_{max}'. The result is that the difference between θ_{max} and θ_{max}' tends to become greater, the greater the distance from the top of the transformer to the oil level, with a resulting increase in the velocity of circulation, which reduces the temperature drop from the coils into the oil, and results in a smaller value for both θ_{max} and θ_{max}', although their difference is greater. The temperature at the bottom of the duct is raised, while that of the oil above the transformer is lowered. Whether or not the average temperature of the windings will be lower for a tall tank than for a short one, with given average oil temperature, it is certain that the maximum temperature at the top of the coils and the temperature of the oil at the top of the tank will be lower, the temperature distribution being more uniform from bottom to top throughout the transformer.

If there is no diaphragm between the outside coils and the tank, the temperature of the oil adjacent to the tank, from the top of the transformer downward, will fall away less rapidly at first, but will come down more rapidly with a curve toward the bottom. In this case θ_{av}' is greater than $\tfrac{1}{2}\,\theta_{max}'$. and the velocity of circulation through the ducts will therefore be reduced, causing a higher temperature rise in the oil passing through the ducts, and also a greater drop from the surface of the coil to adjacent oil.

The effect of the thickness of the duct upon temperature rise will be very different for forced circulation than for natural

circulation. With forced circulation a thin duct will be better than a thick one, since the resulting higher velocity of the oil will give smaller temperature drop from the surface of the coil to the oil. With natural circulation a thick duct will give practically the same condition as to temperature rise as that obtained on an external surface, the rise being less than for a thin duct. Thinning the duct does not, however, cause as great an increase in temperature rise as might be expected, up to a certain point, since, though the temperature rise of the oil while passing through will be greater, this temperature rise tends to produce a higher velocity, and hence to cause a smaller drop from the coil into the oil, as well as to reduce the net temperature rise in the oil itself. When the duct becomes too thin, however, a point is reached where friction becomes serious, so that the curve of temperature rise in the windings, as the duct becomes thinner passes from a flat one to a steep one, probably with rather a sudden deflection. The economy of design resulting from the thin duct makes it desirable that the duct should be as thin as may be, and yet stop short of the steep part of this curve.

The discharge of heat into the duct from both sides, as compared with its discharge from one side only, is an important matter in connection with cooling. It is found that with a duct of given thickness, if the heat is discharged into it from both sides, at a given density in watts per square inch, both the temperature rise of the oil while passing through the duct, and the temperature rise of the coil above adjacent oil, will be smaller than if the heat is discharged into one side of the duct only, at the same density. Thus twice the heat is carried away by the duct, with a smaller temperature rise.

The smaller temperature rise of the oil while passing through the duct, though absorbing twice the heat, indicates that the velocity of flow is more than double, and this accounts for the reduced drop from the coils into the oil. The great difference in velocity in the two cases is accounted for by the friction on the side of the duct where no heat is discharged, which is much greater than when heat is being discharged.

We have so far considered our subject only in connection with coils in which the turns are in a horizontal plane. In shell-type transformers with vertical oil ducts between flat coils, in which the conductors are parallel to the ducts in a vertical direction, conditions are quite different. With the type of winding common in these transformers, the layer insulation is

not in the path of heat flow, and the insulating covering is thin, so that the first important step in the temperature gradient is that spoken of above as step 3, in going from the solid surface to the liquid oil. The equivalent thermal resistance of this step is uniformly distributed throughout the length of the duct, since the rate of oil flow is the same throughout, but this resistance will change with changes in the rate of heat discharge because the velocity of the oil will be different. Now if the heat generated in any part of the coil were all transmitted directly to the oil through that part of the surface which is opposite, the oil would receive heat at a uniform rate throughout its passage through the duct, and the difference between the temperature of the coil and that of the oil would be the same at the top as at the bottom. The temperature at the top part of the coil would therefore be as much greater than its temperature at the bottom as the temperature of the oil leaving the duct is greater than its temperature at entrance. This would result in the passage of a considerable portion of heat downward through the copper, which is a good conductor of heat. This actually takes place, with the effect that more heat is discharged per square inch from the bottom part of the coil than from the top. The temperature rise of the oil in its passage through the duct is, therefore, more rapid in the bottom portion of the duct than in the top, and the temperature drop from the coil to the oil is also greater in the bottom portion of the duct than in the top, on account of the greater density of heat flow. The temperature gradient in the copper from the top of the coil to the bottom is thus reduced, giving a more uniform temperature, as well as a lower average temperature. On the other hand, though the temperature of the oil where it leaves the duct would be the same, if its velocity were the same, since it absorbs the same total heat, yet its average temperature throughout the duct will be greater on account of the larger proportion of heat which it receives near the bottom. This will result in an increase in the velocity of circulation, which tends to reduce both the temperature rise of the oil in the duct and the temperature drop from the coil into the oil, both of these actions affecting further reduction in the temperature of the coils.

We have another important practical case for consideration in connection with the use of disc shape coils, assembled in a horizontal position, with horizontal ducts between. These coils may be wound either in single turn layers, or with several turns

per layer. In the former case practically all the heat will be thrown out into the horizontal ducts, but in the latter the inner and outer layers will discharge considerable heat through layer insulation to the inner and outer cylindrical surfaces. A large portion of the heat will, however, find an easier passage out through the horizontal oil ducts than from layer to layer in the coil. The relative amounts passing out through the two paths will depend upon the circulation of the oil. If the oil is stagnant in the horizontal ducts, it reaches a temperature where it ceases to absorb heat. This condition can only be partial, however, since there is always a tendency for the hot oil to leak out from these ducts, its place being taken by cooler oil.

This type of winding is attractive from the standpoint of design, since if the cooling surface obtained in this manner is sufficiently effective it will give the necessary cooling surface more economically than where this surface must be obtained by unduly lengthening the coils and core in a vertical direction. The relative effectiveness of this method of cooling must be determined by experimental means, the tests covering such points as the effect of the thickness of the horizontal ducts, the presence or absence of internal or external vertical ducts, etc.

The core will not need separate consideration with respect to temperature steps 1, 2 and 3, except to state that the thermal conductivity of iron is such that the interior temperature rise is small, and that, in considering the temperature drop at the surface, we must distinguish between the surface which exposes the edges of all the laminations to the oil, and that which exposes but a single lamination. The relative amounts of heat discharges from these two surfaces, and consequently the magnitude of the temperature drops from the respective surfaces to the oil, will depend somewhat upon the relative thermal resistance in the two directions within the core.

The fifth step in the temperature gradient bears a relation to the density of the heat current and the velocity of oil flow which is similar to that of step 3. The temperature drop from the oil to a surface which is absorbing heat from it, is reduced by forced circulation over this surface in a manner similar to the reduction in temperature drop from the coils to the oil with forced circulation, which has already been described. This involves a comparatively thin duct adjacent to the cooling surface through which the oil must pass.

Before leaving the general subject of the behavior of oil in the process of cooling the transformer, the influence of vis-

cosity should be pointed out. An increase in the viscosity of the oil means an increase in the frictional resistance to its flowing. It results, therefore, in a reduced velocity of circulation, thereby causing an increased drop from the coils and core into the oil, an increased rise in the temperature of the oil while flowing through the ducts, and an increased drop from the oil to the tank. The net result is a higher temperature of the oil at the top of the tank, though its temperature may be lower at the bottom, and a higher temperature in the windings.

The sixth step of the temperature gradient is negligibly small, being due only to the thermal resistance of the metal in the tank. It need not have been mentioned in this discussion except for the fact that something occurs here which often assists very materially in cooling. The top of the tank usually extends several inches above the oil level, while at the bottom of the tank several inches of stagnant oil is usually found, which is practically cold. The tank, especially if of heavy material, as with cast iron, conducts considerable heat upward at the top, and downward at the bottom, thus increasing the area of the external cooling surface. The importance of a given percentage of increase in this surface is all the greater because of the magnitude of the temperature drop from the tank surface to the air.

The seventh step in the temperature gradient, from tank to air, is most important of all, because it is much larger than any of the others. In seeking for engineering economies, the larger items deserve the more careful attention. This step is, therefore, worthy of most careful study.

It has been pointed out above that about half of the heat discharged from a plain tank is thrown out by radiation. Since radiation depends upon the external dimensions of the tank, and not upon its developed surface, the increased cooling obtained with corrugations, cooling tubes, etc., is due to the increase in convection only. This explains why a corrugated surface is so ineffective as compared with a plain one, inch for inch. Comparing a plain tank with a corrugated one of equal dimensions, but with four times the developed surface, if all parts of the corrugated surface are equally as effective for convection as the plain surface, and if 50 per cent of the heat thrown out from the plain tank is convection and 50 per cent radiation the total heat thrown out by the corrugated tank will be 50 per cent$\times$4 plus 50 per cent = 250 per cent of that thrown out by the plain one, so that the watts per square inch thrown out by the

corrugated tank, at the given temperature, are $\frac{250}{4} = 62.5$ per cent of the watts per square inch from the plain one, and the radiation from the corrugated tank is $\frac{50}{2.5} = 20$ per cent of the total heat thrown out.

This result is better than can be expected from a corrugated tank, since in order that all parts of the surface may be equally effective for convection, an equal amount of air must be supplied to every element of surface, to the depth of heat penetration. In order that this may be approximately true for a corrugated surface, the corrugation must be wide and deep, rather than narrow and shallow. Thus with the same outside dimensions, and the same developed surface, the tank with large corrugations will throw out more heat than the tank with small ones, first, because the corrugations contain more air, and second, because the velocity of the air will be smaller in the smaller corrugations on account of the greater friction. And besides the reduced amount of air for absorbing the heat, we probably have here also, as in the oil, an additional increase in the equivalent thermal resistance due to the decreased velocity.

The relative space required for oil and air within the corrugations of a cooling tank is an important consideration. The relative thermal capacities, and densities, of oil and air, easily convince one that the space allowed for air should be large as compared with that allowed for oil, since the product of the thermal capacity and density of oil is many times that of air. Actual measurements show not only that the temperature drop from the oil to the tank is very much smaller than that from the tank to the air, but also that it occurs within much smaller range of the tank. In order to avoid undue effects from friction, however, oil ducts in which heat is discharged by the oil should be more generous than those between the coils, where the oil is absorbing heat.

If they receive the attention which they deserve, each of several phases of the subject which we have outlined will afford material for a lengthy and valuable paper.

Definite figures for the relative values of the various steps of the temperature gradient have not been given since these depend upon the specific conditions of each particular case. It is hoped, however, that the discussion may bring out much definite information, and that this paper may serve as a nucleus for future contributions.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 15, 1911.

DISSIPATION OF HEAT FROM SELF-COOLED, OIL-FILLED TRANSFORMER TANKS

BY J. J. FRANK AND H. O. STEPHENS

This paper is confined to a presentation of the relative merits of the most commonly used designs of tanks for self-cooled transformers. However, since any tank, in addition to dissipating the heat, must fulfill the following requirements, no consideration has been given to discussion of impractical constructions.

In addition to diffusing the heat, a satisfactory tank should, first, be absolutely oil-tight; second, should be of good mechanical construction; third, should occupy small floor space; fourth, should be symmetrical; fifth, should be inexpensive.

Heat is diffused from the surface of self-cooled, oil-filled transformers by three ways; by conduction, by convection, and by radiation. The oil receives its heat from the transformer itself, transfers it to the inner surface of the tank by convection currents, where it is transmitted through the metal to the outer surface of the tank. The ease with which both the oil and the air circulate along the surfaces of the tank contributes to the diffusion of the heat. In addition to the diffusion by the convection currents of air, heat is diffused by direct radiation, and also by conduction from the tank to its support.

The amount of energy that may be dissipated from a tank for a given temperature rise of oil depends upon the extent and nature of the surface exposed to the air. A plain surface per unit of area is the most efficient as the air and oil come in closer contact with it. As the volume or capacity of a transformer varies as the cube of its dimensions, and the surface as the square of its dimensions, the use of a smooth surface for dissipating the

heat in a transformer must therefore be confined to transformers of small capacities involving low losses. Where large capacities and great losses are involved special provision for radiation must be made. The greater the loss, the more complicated the provision naturally becomes.

Various methods have been used to increase the radiating surface of tanks without too greatly increasing the size and cost. A general classification is outlined as follows:

1. Smooth surface.
   (*a*) cast iron or cast steel.
   (*b*) wrought iron or rolled steel.

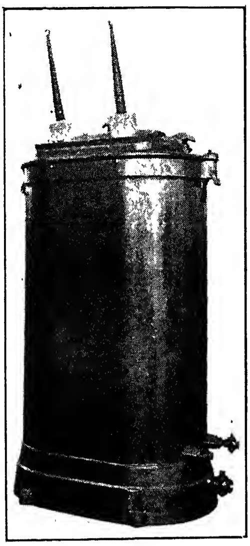


FIG. 1.—Plain cast iron tank

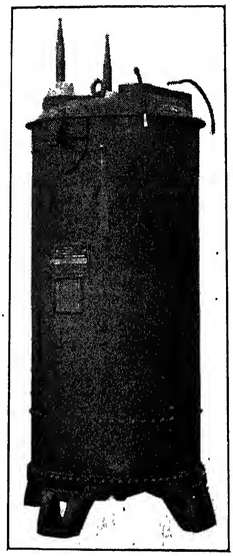


FIG. 2.—Plain boiler plate tank

2. Ribbed surface.
   (*a*) cast ribs.
   (*b*) attached ribs.
3. Corrugated surface.
   (*a*) simple.
   (*b*) compound.
4. External pipes or radiators.

1. Tanks with smooth surfaces having no special provision for radiation are suitable for self-cooled transformers only when the dissipation of small losses is involved. Due to the roughness

of the surface, cast iron will radiate more heat than rolled plate since the roughness increases the surface exposed to the air and oil. In general, the metal in a cast tank is thicker and therefore conducts more heat above and below the band of hottest oil. Fig. 1 shows a plain cast iron tank, and Fig. 2 a plain boiler plate tank.

2. The simplest method for increasing the radiating surface is to attach ribs to the tank. Fig. 3 shows a tank of this type. Wrought iron strips are set on edge at intervals of about one in. (2.54 cm.) around the circumference of a plain, cylindrical,

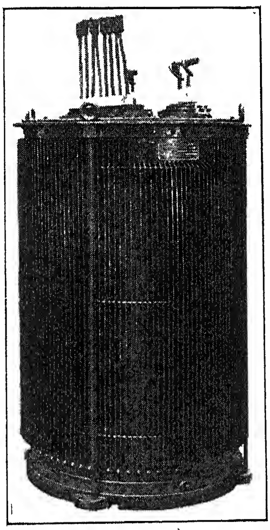


FIG. 3.—Boiler plate tank with attached ribs

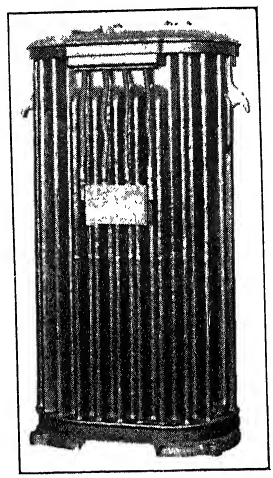


FIG. 4.—Corrugated cast iron tank

boiler plate tank, and are clamped tightly against it. The strips conduct heat from the tank at their bearing surfaces, and air, passing up along them, carries away their heat, and also the heat from the tank surface between the strips. One objection to this construction is the difficulty of obtaining a good contact at the bearing surfaces of the strips and tank, so that the effectiveness of the strips is always somewhat indefinite. In a cast tank the ribs are an integral part of the tank and are hence more effective. They are sometimes cast both on the inner and outer surface of the tank. In either case, the height and thickness of the ribs should be accurately determined, or the weight may be un-

necessarily increased, because it is possible to have quite a difference of temperature between the outside edge of the ribs and the surface of the tank if the ribs are not properly proportioned.

3. The most generally used method for increasing the peri-

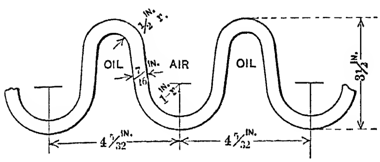


FIG. 5

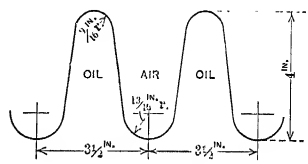


FIG. 7

phery of a tank is to corrugate or flute the surface. By this means, the surface may be increased to several times that of a plain tank of the same over-all dimensions. Tanks of this type may be either of cast iron or of sheet metal. Fig. 4 shows a corrugated cast iron tank, and Fig. 5 gives the dimensions of its corrugation.

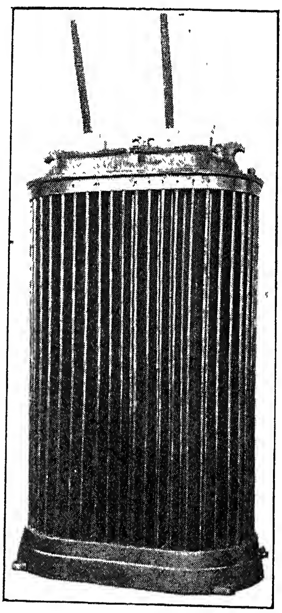


FIG. 6.—Simple corrugated steel tank

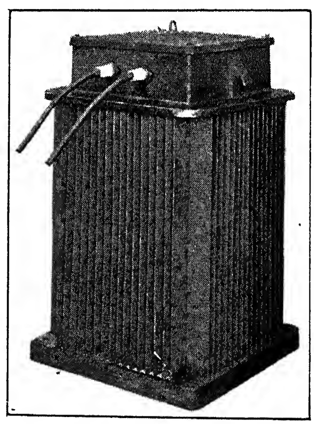


FIG. 8.—Corrugated steel tank—*V* corrugations

Figs. 6 and 7 show a form of corrugated steel tank very commonly used. By referring to Figs. 5 and 7, it will be noted that the space within the corrugations occupied by air is greater than the space occupied by oil. Figs. 8 and 9 show a corrugated

steel tank with simple V corrugations with equal spaces for air and oil. Figs. 10 and 11 show a tank with rectangular corrugations.

A large number of modifications of these forms of corrugations have been used, but, as the capacities of transformers become

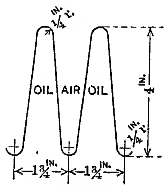


FIG. 9

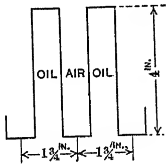


FIG. 11

larger, and the losses high, it becomes expedient to adopt more complicated surfaces in order to keep down the size and cost of the tanks. A recent and important development along this line is a tank with compound corrugations. It is obtained by double-corrugating the surfaces so that it will be made up of

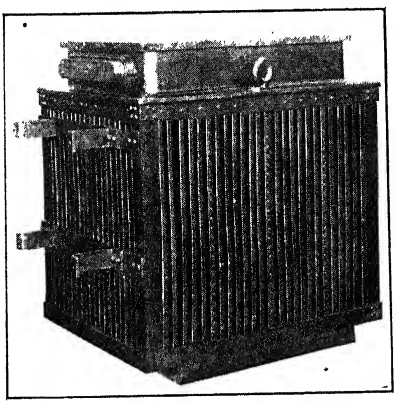


FIG. 10.—Corrugated steel tank—rectangular corrugations

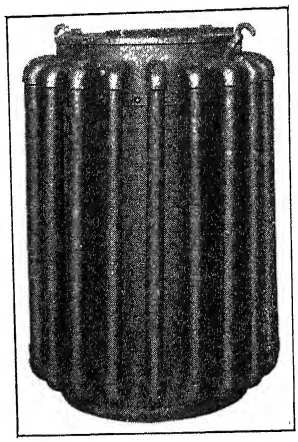


FIG. 12.—Boiler plate tank—external radiating pipes

major and minor corrugations. The minor corrugations may be similar to the preceding illustrations and the major corrugations are made up of a number of the minor corrugations.

4. Examples of another scheme coming into practice are shown in Figs. 12 and 13. These tanks have auxiliary pipes or radiators apart from the transformer tank proper. Fig. 12 is a cylindrical

boiler-plate tank with external radiating tubes, and Fig. 13 is a large corrugated steel tank with external corrugated cooling boxes. Hot oil enters the auxiliary pipes at the top, cools and sinks to the bottom. The method does not differ materially from the ordinary tanks, excepting the definite path provided for the circulating oil. Fig. 14 shows the circulation in an ordinary tank with a barrier between the transformer and the tank wall. This confines the circulation to a definite path down along the cooling surface of the tank. Local eddy currents in the oil are thus avoided and the circulation is much more effective.

The curves in Fig. 15 were plotted from a large number of tests made to determine the oil temperature rise at various losses for different kinds of tanks. They show the relation between the temperature rise of the oil at the top of the tank and the watts loss per square inch of tank radiating surface.

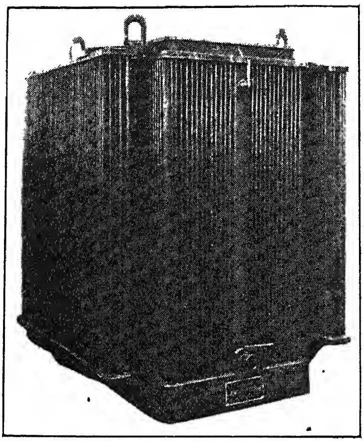


FIG. 13.—Corrugated steel tank—external radiating boxes

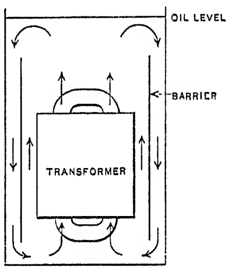


FIG. 14

The oil temperature rise of a transformer may be determined by means of these curves when the losses are known and the radiating surface of the tank has been calculated. The radiating surface used for these curves consists of the total wetted surface of the tank exclusive of the bottom, since the radiation from the bottom would be extremely small in any case. The actual radiating surface of a tank varies with the temperature of the oil, since the oil expands with the heat, and rises higher in the tank, thus increasing the effective surface. For uniformity, the oil level at 25 deg. cent was used for calculating the radiating surface and the curves take care of the differences due to oil expansion.

The oil temperature curves in Fig. 15 may be expressed by an equation of the following form:

$$T = K\,W^p$$

in which T is the temperature rise above 25 deg. cent., W is the average watts per square inch of tank surface, and K and p are constants depending upon the form and material of the tank and the conditions of the test.

All of these curves were plotted with the watts per square inch corresponding to the actual losses in the transformers at the operating temperatures.

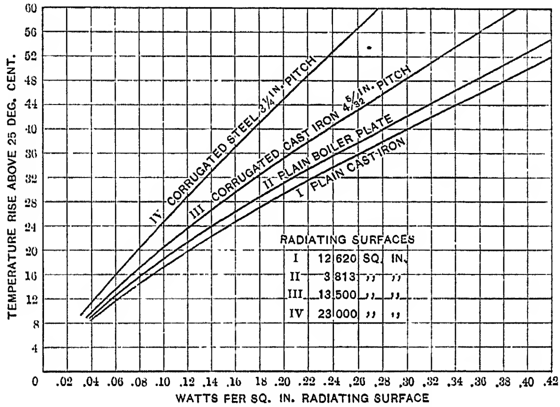


FIG. 15.—Maximum oil temperature rise for transformer tanks

The dimensions of these tanks are given in the table.

	Thickness of metal	Floor space	Height	Radiating surface	Illustrations
Plain cast iron....	½ in.	5 ft. 2 in. by 3 ft. 4 in.	7 ft. 7 in.	12620	Fig. 1
Plain boiler plate..	¼ in.	2 ft. 9 in. by 1 ft. 9 in.	4 ft.	3813	
Corrugated cast iron	7/16 in.	3 ft. 7 in. by 2 ft. 4 in.	6 ft. 8 in.	13500	Figs. 4 & 5
Simple corrugated steel............	1/16 in.	4 ft. 5 in. by 2 ft. 11 in.	6 ft. 5 in.	23000	Figs. 6 & 7

The curve in Fig. 16 gives the results of tests on the tank shown in Fig. 12. The radiating surfaces of the pipes and the tank proper are given on the curve.

Comparative tests on a number of tanks with attached ribs similar to the one shown in Fig. 3 indicate that the rise of a tank is about 20 per cent lower with the ribs than it is without

them. For example, if a plain tank runs at 50 deg. rise, it may be made to run at 40 deg. rise, with the same losses by attaching ribs to it, similar to Fig. 3.

A number of tests were made upon four special tanks having the same over-all dimensions but with different pitch of corrugations. The depth of the corrugation was 4 in. (10.16 cm.) for each tank. Unlike the corrugations in the previous tests, the space occupied by oil and air within the corrugations was equal. The lateral dimensions of the tank to the outer portion of the corrugations was $39\frac{1}{2}$ by $39\frac{1}{2}$ in. (one m. sq.). The height was 8 ft. (2.43 m.) and the oil level 5 in. (12.7 cm.) below the top, making the height of the wetted surface 91 in. (2.2 m.). These tanks were very high for their lateral dimensions, and the heating units being some distance up in the tanks, there was considerable dead oil in the bottom, so that there was very little radiation from the lower part of the tank. Thermometer tests indicated that about 11 in. (27.9 cm.) should be subtracted from the height, making the effective height 80 in. (2.02 m.).

The table gives the radiation at a temperature rise of 40 deg. cent. taken from the test curves.

Tank number	1	2	3	4
Pitch of corrugations, in......	$1\frac{3}{4}$	2.1	$2\frac{5}{8}$	3.50
Total wetted surface, sq. in...	56,900	48,300	39,200	30,300
Effective radiating surface, sq. in........................	50,000	42,500	34,500	26,600
Kw. radiated at 40 deg. cent. rise........................	5.8	5.43	5.13	4.85
Apparent watts per sq. in.....	0.102	0.112	0.131	0.160
Watts per sq. in. effective....	0.116	0.128	0.149	0.182

The tests indicate that the gain in radiation to be obtained by reducing the pitch of the corrugations so as to increase to total surface is entirely disproportionate to the increase in surface. While tank No. 1 has a radiating surface 88 per cent greater than tank No. 4 it radiates only 19.6 per cent more losses at 40 deg. rise in the oil. The following conditions combine to cause this:

For two tanks of the same dimensions, the increase in surface obtained by closer corrugations has no effect upon direct radiation, so this component of radiation remains unchanged.

Air flowing in at the bottom of the corrugations receives heat from the tank and passes up through the corrugations with an

increasing velocity as its temperature rises. More air must flow in at the side along the corrugations to make up for this increased velocity. If the corrugations are pressed closer together so that the ratio of air space to radiating surface is smaller, the air would have to flow at a greater velocity to carry off the same watts per square inch. Air friction varies as the cube of its velocity and hence it will not flow at a sufficient velocity to carry off the same watts per square inch from the closer corrugations.

In addition to the causes outside of the tank, the oil will not circulate as freely over a closely corrugated surface because of the increased friction, but the effect within the tank is much

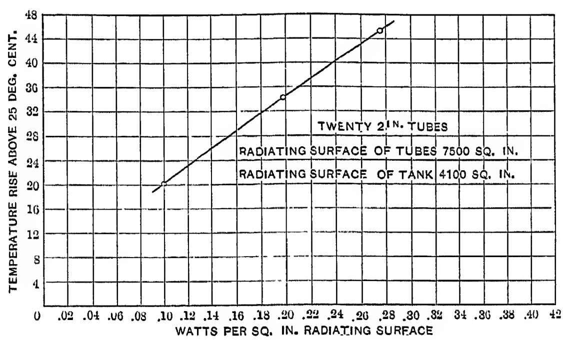


FIG. 16.—Round boiler plate tank—external radiating tubes—oil temperature rise at top of tank—No. 6 transil oil

smaller than it is without, principally because the temperature drop from the oil to the tank is much smaller than from the tank to air.

The tanks used for these tests were very high for their lateral dimensions, and experience indicates that narrow and deep corrugations may be used to a greater advantage on lower tanks, principally because the air currents will not have to acquire such high velocities.

A principle that is suggested by the foregoing discussion is that the most effective corrugation will not have equal oil and air spaces but the air space will be much greater than the oil space. This idea has been used in the design of transformer tanks for a number of years. It has the further advantage of reducing the oil required.

It was stated in the beginning that the nature of the radiating surface has an effect upon its radiating properties. This was shown in the tests on the cast iron and the boiler plate tanks.

In addition to the material itself, the color and character of the paint has some effect upon the radiation of tanks, especially when they are exposed to the direct rays of the sun. A number of tests were made to determine whether or not this effect was appreciable. The tests were made on transformers sizes 5 to 50 kilovolt-amperes, with tanks painted with black, white enamel, and aluminum paint, respectively. The transformers were so placed that tanks were exposed to the direct rays of the sun all day long and tests were made only in clear weather.

The results of these tests indicate that tanks painted with white enamel or aluminum paint run several degrees cooler in the daytime and slightly warmer at night than tanks painted with black paint. Inasmuch as such transformers are usually loaded at night, it would appear that there is no appreciable practical benefit to be derived from the use of white enamel or aluminum paint and, moreover, it is doubtful whether the effect would be permanent, due to blackening of the paint after exposure to the weather.

The matter is, however, of interest as an indication of the effect of changes in conditions of operation upon the dissipation of heat from transformer tanks.

One item of primary importance in designing transformer tanks is the cost. The only satisfactory basis of comparison is the cost per kilowatt loss radiated at a given temperature rise of the oil. Comparison should be made only between tanks that will dissipate approximately the same losses, because the cost per kilowatt loss varies with the size of the tank as well as with its material and construction. The following table gives average comparative costs of tanks designed to radiate from one to three kilowatts loss at 40 deg. cent. rise in the oil, plain cast iron tanks being used as the standard of comparison:

Plain cast iron	100
Plain boiler plate	97
Corrugated cast iron	93
Corrugated steel	61

The above figures do not include the cost of oil and if this were added the difference in cost between the plain and corrugated tanks would be greater.

For larger losses a similar comparison would show an increased advantage in favor of the corrugated steel tank, and other more complicated surfaces, and if the losses are still further increased the plain tank becomes quite out of the question.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February, 15, 1911.

PROBLEMS IN THE OPERATION OF TRANSFORMERS*

BY F. C. GREEN

The slightest puncture of a transformer means that it must be dismounted entirely before repairs can be made. The oil must be drawn out, the leads disconnected, and the structure moved to a location where there are facilities for hoisting. Moreover, there is interruption of service with consequent loss of revenue and impairment of prestige. At its best, transformer repairing in a station does not inspire a feeling of enthusiasm for the electrical arts. And yet the damaged coils with their slime are the starting point of progress along manufacturing lines, as well as of progress along those lines that lead to the consideration of electric stress, line oscillations, temperature gradient, and other similarly advanced features of the science.

Thus, the main problems in the operation of transformers are to select those best designed to meet the service requirements and to give them such care in their installation and such attention in service as will minimize liability of unnatural weakness or abnormal strains. Important problems arise in the adaptation of transformers to a variety of service.

INSTALLING

The high voltages used now make necessary a large amount of solid insulation between high-tension and low-tension coils and between coils and laminations. The present manufacturing practice calls for solid insulating materials that are fibrous. These cannot be so treated that they will not absorb at least a small amount of moisture from the air during shipment or storage. Occasionally, facilities for handling transformers at the station

where they are to be installed, admit of shipping with the oil in them, but as a rule the transformers and oil must be shipped separately. Hence the necessity for drying arises.

The full effect of the process used should extend to the fibrous insulating materials as well as to the coils. In fact, a coil has to withstand normally a voltage not exceeding 6000 or 7000 volts and usually the voltage is much lower than this, while the voltage between windings may reach a normal value of 100,000 volts in modern transmission systems. Furthermore, coils are more easily dried than the insulation between windings. The usual short-circuit run heats the coils but the effect does not extend through the heavy insulating shields, because the heat is carried up by the air circulating through the spaces between the coils and shields, and is given up to the cover and tank. The circulation of large quantities of heated air is an easy and effective process of drying. Where the tank is suitably constructed, the vacuum process of treating the transformers filled with oil, may be used. In this case the heat must be so applied as to maintain a uniform temperature of oil throughout the tank, and the degree of temperature and of vacuum must be so related as to cause the moisture to vaporize. Unevenness of temperature makes ineffective the vacuum process of drying without oil in the tank.

Oil may be dried by blowing heated air through it or by holding it at a temperature that will vaporize moisture, either at atmospheric or a lower pressure, such as is obtained in the vacuum process. The adaptation of the filter press with blotting paper to the treatment of oil, has proved to be most satisfactory. There is no danger of injury from excessive temperature, and both the moisture and sediment are removed. In case it should be found desirable, oil may be treated by means of the filter press without taking transformers out of service.

Causes of Failures

If a high-voltage transformer is built with a safety factor of ten instead of the usual factor of two, it avails nothing in case of neglect to properly install it, assuming it to have become moist in shipment. It is equally true that this same transformer, being properly installed, is about as likely to break down as the one with the safety factor or two. This brings up a consideration of the parts of the transformer most exposed to effects of conditions that practice has shown to be dangerous. Abnormal

voltage conditions are responsible for almost all transformer failures. Examination of the damaged portions has shown that it is not the total abnormal voltage impressed that is dangerous, but that the disturbance of the voltage equilibrium within the windings is responsible for a large majority of the operating troubles attributable to transformers. Thus, the percentage of punctures between high-tension and low-tension windings, or between the windings and laminations, is negligible as compared with the percentage of punctures between turns, or between portions of the same winding.

The standard practice for the potential test of high-voltage transformers is to apply twice the rated high-tension voltage between the high-tension winding and the low-tension connected to the iron. The induced voltage test is the application of twice the rated voltage to one of the windings. The purpose of the induced voltage test is to determine whether the various portions of a given winding are properly insulated from one another. This test of course subjects adjacent turns to twice the normal voltage between turns, but, as will be seen, this does not mean much except in cases of mechanical defects, which are rare.

Assume that a 100,000-volt transformer for transmission service has a normal turn voltage of 60 volts. The value of the test voltage between the high-tension winding and other parts, is 200,000 volts. To break down the transformer under this test would require, say, between 220,000 volts and 250,000 volts. Under the induced voltage test, the voltage between turns is 120 volts. But the voltage required to puncture the insulation between turns, is found to be around 5000 volts. Nevertheless, as previously pointed out, almost all failures of transformers of this kind occur between turns. Thus in the operation of transformers it is found that the designer must attempt to meet the difficult problem of taking care of a voltage between turns that may range from 60 volts under normal conditions to 5000 volts and above under abnormal conditions of line disturbances, that may not appreciably increase the line voltage, but that affect the equilibrium of the voltage within the winding to the extent of concentrating a very excessive potential across a small percentage of the total turns.

While modern lightning arresters successfully limit to a safe value the voltage between phases, and between the line and the ground, they are not adapted to the protection of the trans-

former against the concentration of a dangerous voltage upon a small percentage of the total winding.

The portions of the winding most liable to excessive voltages of this kind are towards the line ends; but this is not always the case, the relative location of the danger portion depending upon the nature of the disturbance of the voltage equilibrium. However, the percentage of transformer failures is small; but there is reason to believe that it can be reduced to an inappreciable value by means of increasing the effective insulation between parts of the winding most liable to damage, and by means of reducing line disturbances to a practicable minimum. Also, the transformer is less liable to the effects of line disturbances where its capacity in microfarads is small.

Another cause of destruction of transformers is their connection to bus bars of generators having a total capacity many times greater than that of the transformer. Before this kind of trouble appeared, with the concentration of large amounts of power, it was desired and specified that the transformer regulation should be a minimum. To meet this specification a low reactance was necessary. Thus in many instances the impedance voltage was limited to from 2 to 4 per cent. If a transformer is assumed to have 3 per cent impedance voltage, and to be backed with sufficient generator capacity to maintain normal voltage, a current about 30 times normal will flow when a feeder leading from the transformer becomes short circuited. The flow of such a current in a medium or a large sized transformer produces electromagnetic stresses of many tons. The forces exerted are in such relation to one another as not only to flare the ends of coils over the supports for holding them together; but also to twist and distort the individual coils.

This sort of trouble has been cured by inserting separate reactance in circuit with transformers having low inherent reactance, by designing for higher inherent reactance, and by increasing the surfaces of coil supporting strips. Experience has shown that a quick-opening switch is not effective in protecting a transformer against the distorting forces of heavy current rushes in cases of short circuited lines.

Care in Operating

Where artificial cooling is used, the circulation of the cooling medium should not be neglected; the transformer cannot run

continuously even under no load with the circulation shut off. The cooling coil of a water-cooled transformer is liable to become stopped up with weeds and grass, which restrict the flow of water, or a coating of dirt and mud may form inside the coils, decreasing the effectiveness of the cooling. Occasionally chemical action takes place between the water and the metal of the coil resulting in a formation that lessens the effective cross section. Systematic observation of the flow and temperature of the water and of the temperature of the oil in the transformer, will give an indication of approaching danger from any of these sources.

Another feature of cooling that sometimes leads to a critical condition is the forcing of the circulation on occasions of heavy overload. If a very large amount of cold water is forced through the coil, and the coil is in good condition as regards its internal surface, then the temperature of the oil is maintained at a value, under a very heavy overload, that gives no indication of the temperature of the transformer windings. It has been demonstrated in service that it is possible to seriously overheat the windings without unduly raising the temperature of the oil.

The oil transformer that relies upon tank surface or its equivalent, for cooling, is generally considered as requiring no thought in its housing, or attention in service. It is supposed to be self-cooling, regardless of surroundings that do not admit of the free escape of the heat.

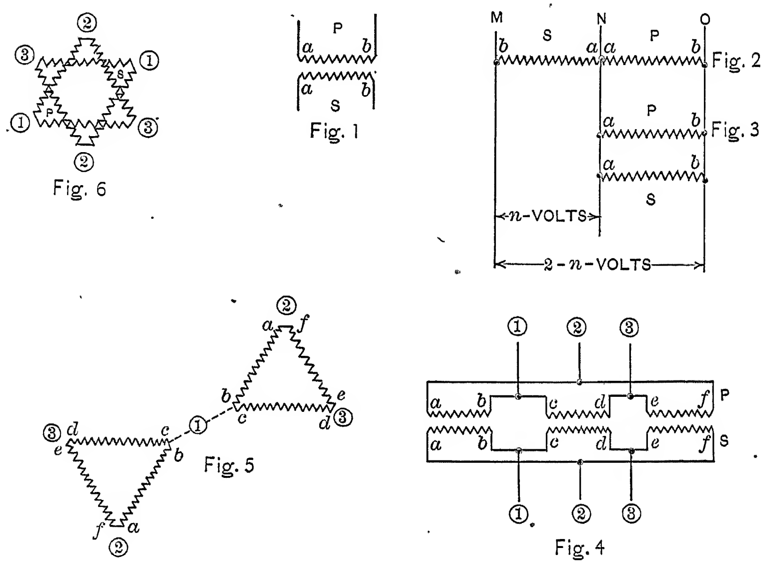
If six 500 kilovolt-ampere transformers are found operating in a room 15 ft. by 30 ft. by 15 ft. (4.6m. by 9.1m. by 4.6m.) it is generally expected that they will operate satisfactorily regardless of whether or not there are openings in the room for the circulation of air. Now assuming the losses to be 2 per cent, there are 60 kw. of energy to be radiated. This is equivalent to 80 h.p. Imagine an 80-h.p. boiler making steam at its normal rate, for a room of the dimensions given above, on a hot summer day; this will give an idea of the necessity of proper ventilation of the room and of the spacing of the transformers. To limit the temperature rise of the air in the room to 5 deg. cent., would require the circulation of approximately 21,000 cu. ft. (594 cu. m.) of air per minute. The air in the room would have to be entirely renewed three times per minute.

It should not be assumed that the manufacturer is free of responsibility in questions affecting the operation of transformers. It is not only necessary to have reliability and effi-

ciency, but the transformer case should be built so as to facilitate crude handling as well as crane handling; and connectors for changing ratio should be easy of access and manipulation.

Connections

Frequent occasion arises for the determination of the effect of a certain combination of transformers. It is an easy matter for the operator to determine whether a combination is correct or not, by simply applying the voltage; but in case the test



Sketch A

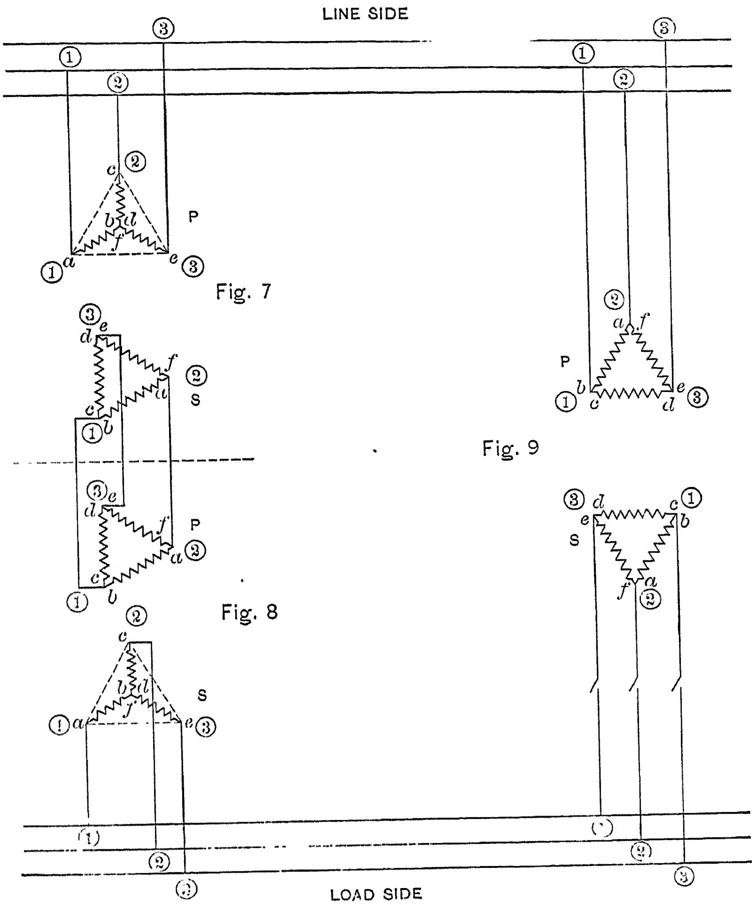
should prove it to be wrong, it is not always easy to figure out what the correct combination is.

The following treatment of this question is based upon instances that have arisen in connection with systems in various parts of the country. Experience has shown that there are two main divisions of this question; combinations that show their effect immediately on being energized, and combinations that do not show their effect immediately on going into service, but develop objectionable and dangerous effects under peculiar conditions.

We will take up some instances illustrating the first mentioned

division. Sketch B shows a combination that it was desired to use. The "line side" represents the high-tension or transmission side of the transformers, and the "load side" represents the low-tension or distributing side.

A three-phase problem of this kind embodies phase rotation



SKETCH B

and phase position. For simplicity, we will begin with a single-phase combination shown in Sketch C, similar to the three-phase combination shown in Sketch B. There is this difference between the three-phase and single-phase combination: the single-phase combination will always have the same phase rotation if the phase position is the same, while the three-phase com-

bination may have the same phase rotation but a different phase position.

Referring to Sketch A, Fig. 1 represents a single-phase transformer with two primary leads and two secondary leads brought out of the transformer relatively as shown. Assume for simplicity that the ratio is 1:1. Having in mind that the ratio is 1:1, whether the *a* points of the primary and secondary can be connected together and the *b* points together, without causing a short circuit, depends upon polarity; or in other words, upon whether, beginning with the *b* points, the windings follow the same direction around the core or opposite directions. If they extend in opposite directions, Fig. 2 shows the relation. *a b* of the secondary being wound opposite, lies 180 deg. from *a b* of the primary. Thus, by connecting the *a* points there is a voltage of $2n$ volts between the *b* points.

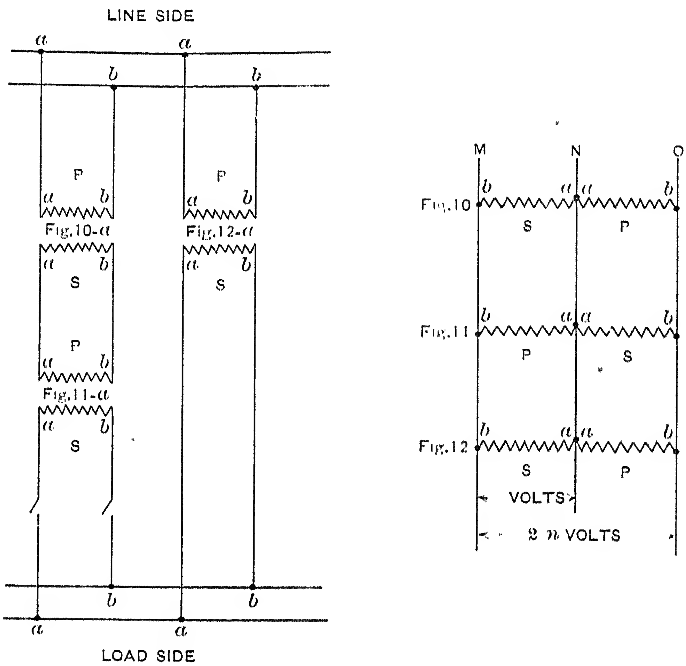
If the two windings lead from the *b* points in the same direction around the core, Fig. 3 shows the relation. Thus, there is 0 voltage between the *a* points and between the *b* points, having n volts between *a* and *b*. This means that the *a* points can be connected together and the *b* points together without causing a short circuit.

Referring now to Sketch *C*, and assuming that the single-phase transformers shown have primary and secondary wound in opposite directions around the core, it is found that the *a* points cannot be connected together and the *b* points cannot be connected together, as shown in Figs. 11-*a* and 12-*a*, without causing a short circuit. All that is necessary in this single-phase instance is to cross the leads of any one of the windings of any one of the transformers shown. This crossing of course would be done outside of the tank. Thus, *a* of the secondary, Fig. 11, may be connected to *b* of the secondary, Fig. 12, and *b* to *a* for the multiple connection.

If it is assumed that the polarity is such that the windings extend in the same direction around the core, then the combination of transformers as shown in Sketch C would be feasible. Furthermore, it would be feasible with any number of transformers in one of the multiple circuits as compared with the number in the other circuit.

The combination referred to in Sketch B contemplated the use of single-phase units with windings in opposite directions. It is seen in Figs. 4, 5 and 6 Sketch A that in a three-phase combination of transformers, the fact that the phase rotation

is the same does not mean that the phase position is the same. Assuming a given three-phase line voltage impressed on the points 1, 2 and 3 of the primary, Fig. 4, there results the phase relation shown in Fig. 6 between the primary delta and the secondary delta. In other words, with transformers whose primary and secondary windings lead in opposite directions around the core, connected delta to delta, the primary delta makes a six-phase relation with the secondary delta. The method of arriving at this relation is shown in

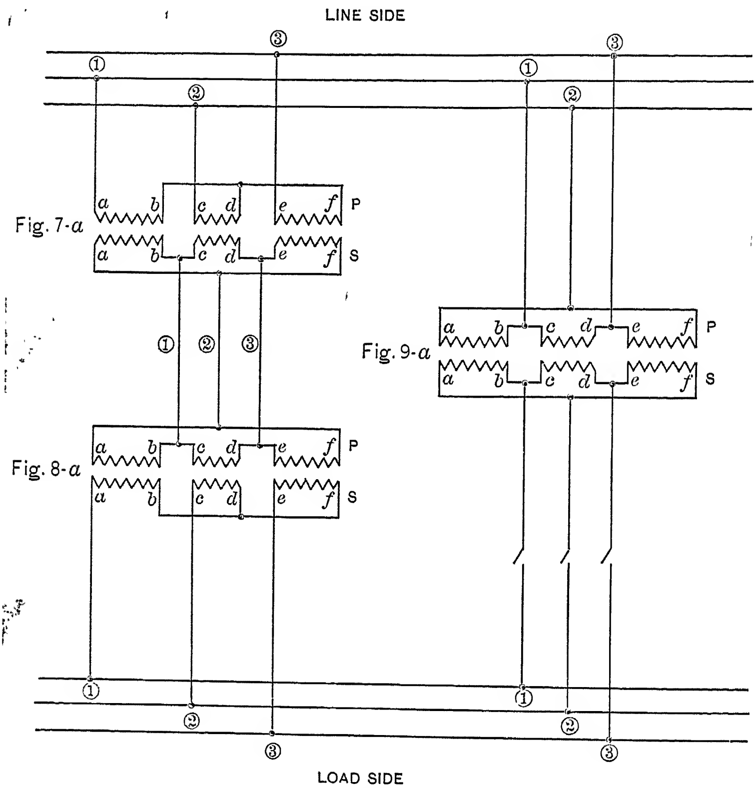


SKETCH C

Fig. 5. Each secondary winding is shown revolved 180 deg. from its primary, and the points connected together in this figure for making both the primary and secondary deltas, are the same as the points shown connected together in Fig. 4. Fig. 6 is the same as Fig. 5 except that in Fig. 6 the secondary is shown superposed on the primary as it would actually be in practice. If we assume that the primary and secondary windings of the individual units are wound in the same direction around the core, then the points of the secondary

delta would coincide with the points of the primary delta and would not have the six-phase relation. Another feature noticeable in Fig. 5 and Fig. 6 is that the points 1, 2 and 3 of the primary and of the secondary, while not coinciding, show the same rotation.

We are now prepared to take up the main question as to whether the combination shown in Sketch B is feasible. Sketch



SKETCH D

D shows the individual transformer connections corresponding to the combination shown in Sketch B. The points 1, 2 and 3 of the primary represent the impressed voltage in Sketch B, and the transformer terminals upon which this voltage is shown to be impressed in Sketch D. Thus, of necessity, the primary points 1, 2 and 3 of Fig. 7 and Fig. 9 must coincide, since the corresponding numbers of the figures represent identical voltage

points. The question is: what relation shall we find where the two multiple circuits come together on the load bus?

Keeping in mind that the primary and secondary are wound in opposite directions around the core we find in Fig. 7 that the combination of secondary windings, each shown revolved 180 deg. from its primary, gives a delta lying in such a position as to bring together the points shown connected in the secondary of Fig. 7-*a*. The delta in Fig. 7 cannot lie in any other position than the one shown, and at the same time bring together the points shown connected in Fig. 7-*a*. The relation between pri-

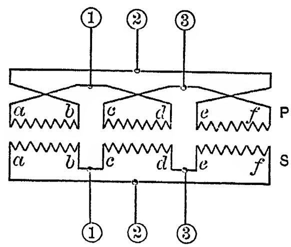


Fig. 9-*b*

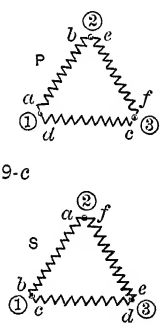
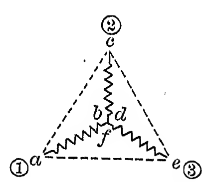


Fig. 9-*c*



S. OF Fig. 8 REPRODUCED

SKETCH E

mary and secondary, therefore, is fixed. The primary of Figs. 8 and 8-*a* is the same as the secondary of Figs. 7 and 7-*a*, the delta of Fig. 8 lying in the same position as the delta of Fig. 7. The individual secondary windings of Fig. 8 are shown, each 180 deg. from its primary, to form a definite Y corresponding to the connections shown in Fig. 8-*a*. Figs. 9 and 9-*a* show a delta-delta combination of single-phase transformers of standard polarity. It has already been pointed out that the primary voltage figure represented by points 1, 2 and 3, Fig. 9, must coincide with the primary voltage figure represented by points

1, 2 and 3 of Fig. 7. In the secondary of Fig. 9 each winding is shown arranged 180 deg. from its primary, making a delta with points connected together as shown in Fig. 9-*a*, such that, if superposed on the primary as it actually is in practice, would give a six-phase relation between the primary and secondary.

The secondary points 1, 2 and 3 of Fig. 8 and the corresponding points of Fig. 9 are seen to be fixed in their positions. According to the conventional practice of connecting the two circuits, as shown in Sketch D, in multiple, the points numbered 1 would be connected together, the points numbered 2 connected together and the points numbered 3 connected together. But if we refer to Sketch B we find that in superposing Fig. 8 upon Fig. 9, the points 1, 2 and 3 do not coincide, but make a six-phase combination, which if connected together will give a short circuit on the impedance of the combination, the corresponding points of the two figures being 180 deg. apart. Furthermore, they cannot be made to coincide by varying any of the connections to either the high-tension or low-tension line.

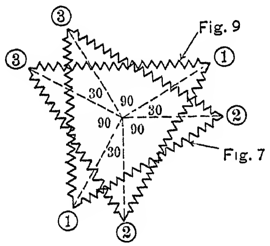


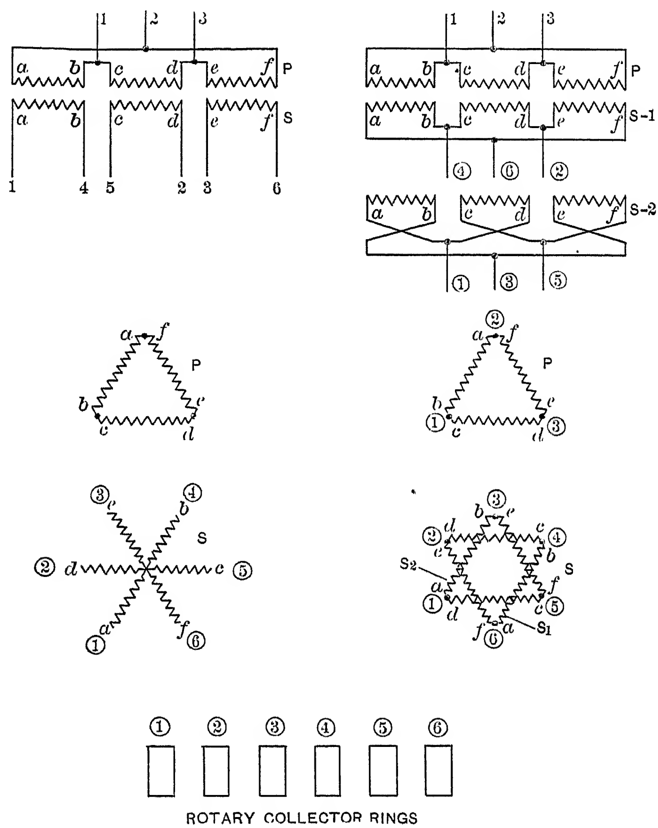
Fig. 13

By reversing the primary leads of the individual transformers of Fig. 9-*a*, Sketch D, as shown in Fig. 9-*b*, Sketch E, the points 1, 2 and 3 of the secondary of Fig. 9 are made to coincide with the points 1, 2 and 3 of the secondary of Fig. 8, as shown in Fig. 9-*c* and the secondary of Fig. 8 reproduced in Sketch E. A number of other problems that have arisen in practice may be explained in detail by the reasoning given for this instance.

It is generally understood that a Y-delta combination cannot be run in multiple with a delta-delta combination. Referring to Sketch B, the relations between two such combinations are shown in Figs. 7 and 9. Fig. 13 is used to show the secondary of Fig. 7 superposed on the secondary of Fig. 9. as it would actually be in practice. Referring to Sketch D, if the operator desires to make the trial of connecting the bank of Fig. 7-*a* in multiple with the bank of Fig. 9-*a*, he would connect the 1 leads together, the 2 leads together and the 3 leads together. But these corresponding points as shown in Fig. 13, are from 30 to 150 deg. apart. Furthermore, the phase rotation is reversed, so that to connect the corresponding points together would give

a short circuit. It is commonly said that the secondary deltas in this instance are 30 deg. apart, but this statement is based upon the location of the points with the same phase rotation, and not upon the points that would ordinarily be connected in service.

Sketch F shows the usual combinations of three transformers for obtaining a six-phase voltage for synchronous converters.

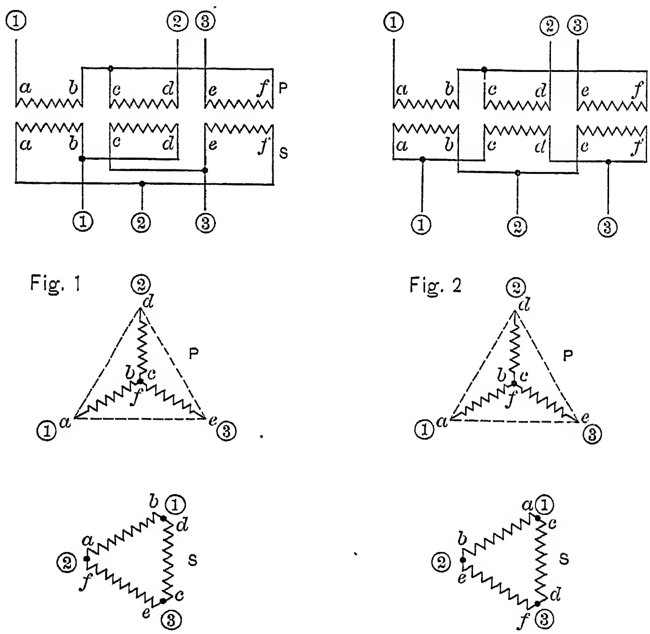


SKETCH F

Fig. 1 of Sketch G shows a three-phase transformer that was desired to be operated in multiple with the one shown in Fig. 2. The connections were as shown, and it was known also that in the case of Fig. 1, the individual phases have their windings wound in the same direction around the core, while the individual phases of the transformer shown in Fig. 2, have their

primary and secondary windings wound in opposite directions around the core. It is seen from the sketches that the deltas of the transformers coincide and that the phase rotation is the same for both transformers.

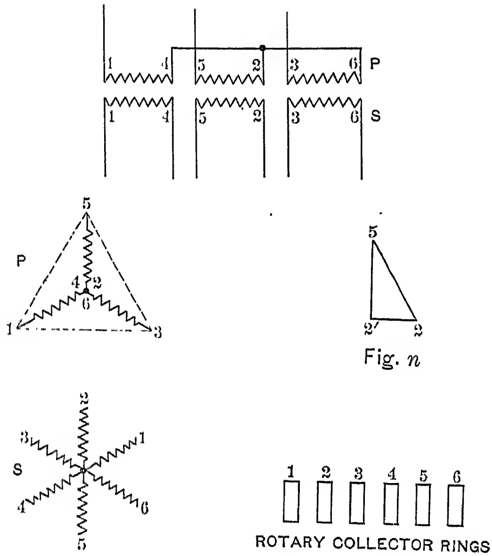
A study of the foregoing examples will show that, in order that two banks of transformers may operate in parallel, it is not only necessary to have the phase position of relative banks the same, but also to have the phase rotation the same. This phase rotation is a matter of the order in which the legs of the circuit



SKETCH G

are brought away from the transformers, and may be said to be determined by the direction in which an induction motor would run when it is connected to a circuit in a fixed manner. The phase rotation is not changed by changes in polarity nor in going from primary to secondary in a delta-delta or Y-Y combination, provided the legs of the circuit are brought away in the same order on both sides, according to conventional practice. In the case of a Delta-Y or Y-Delta combination, conventional practice, in connecting to the circuit. reverses the phase rotation in going from primary to secondary. This is illustrated in Sketch

B, Fig. 7, where the voltage points 1, 2 and 3 are in reversed direction around the triangle of the secondary from that found on the primary side, or on the secondary side of Fig. 9. Reversed rotation accounts for the varying degrees of voltage difference obtained between the 1 points, 2 points and 3 points of Fig. 13. If, in Fig. 7 Sketch B, 1 and 2 legs of the secondary circuit were interchanged, the discrepancy in phase rotation would be corrected and a uniform angular difference (30 deg.), of phase position between respective points would be found in Fig. 13.



SKETCH H

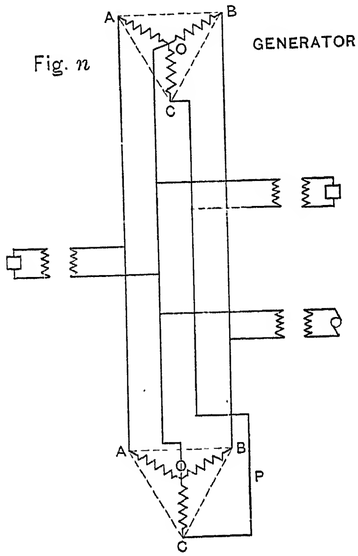
CONNECTIONS THAT DEVELOP TROUBLE

Sketch I shows a combination of transformers and generator commonly used in large cities. In some instances the triple frequency voltage established by the generator has been of sufficient value to cause heavy triple-frequency current to circulate in the delta of transformers for three-phase service. It is understood that the triple-frequency voltage does not appear between lines but only between lines and the neutral point. (See paper by J. J. Frank, PROCEEDINGS A. I. E. E., March, 1910). Therefore, the fourth wire connected to the neutral point for the distributing system, admits the circulation of the objectionable current in the windings of the transformers

connected as shown in Fig. *m*, Sketch I. This no-load current has been known to reach values ranging from 50 per cent to 90 per cent of the full-load current.

This objectionable current has been easily eliminated by simply disconnecting the fourth wire from banks of transformers used for three-phase service. If it is desired to ground the neutral of the distributing system the generator neutral may be grounded.

Fig. *n*



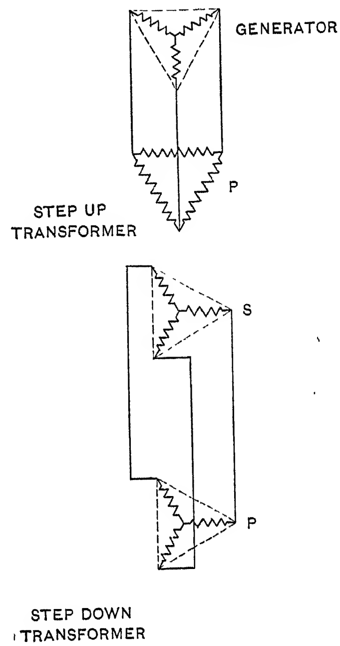
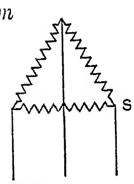
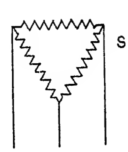


Fig. *m*



SKETCH I

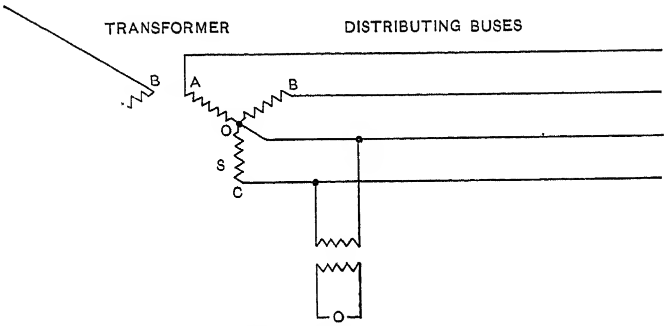


SKETCH J

This keeps down the static electricity usually noticed in stations where the neutral is not grounded. It is not necessary to ground the neutral of the bank of transformers for the motors.

Sketch H shows the combination of transformers for six-phase split-pole converter service. There are two sources of triple-frequency current encountered in practice. In Sketch I it was shown that the triple-frequency effect originated in the

generator. In Sketch H we have an instance of the appearance of triple frequency effect that results from the nature of the transformer. That is, any transformer may be so connected with other transformers as to show the triple-frequency effect inherent in all transformers. There was occasion to measure the secondary voltages with normal voltage impressed on the primary of the transformers shown, before the switch between the transformer and converter was closed. Each of the secondary voltages was found to be about 10 per cent higher than it was rated. Thus, it appeared that the transformer ratio was incorrect, but this was not the case. Readings taken from the points 1, 5 and 3 to the neutral point showed that each of the leg voltages was greater than that corresponding to the line voltage from 1 to 5, etc. The neutral connection was found to have a different potential from that of the earth, notwithstanding



SKETCH K

that the leg voltages were equal. The voltage diagram of a leg is shown in Fig. *n*, Sketch H. 5-2 is the measured voltage and 5-2′ is the leg value corresponding to the line voltage; so that 2′-2 at right angles to 5-2′ is the value of the triple-frequency component. This value holds true for each of the legs, and is best understood by considering the leg values in a plant at right-angles to a line passing through the true neutral point, the observed neutral being a point in the line out of the plane of the legs. Thus, if the measured leg voltage is found to be 10 per cent greater than the value corresponding to the line voltage, then the triple-frequency would have an actual value of about 46 per cent, assuming the true leg value to be 100 per cent and the observed value 110 per cent. This means that if the secondary windings are connected in delta and one corner of the delta is opened the voltage found at the open corner is

about 40 per cent greater than the rated voltage. The ratio of transformation was found to be correct, comparing the secondary voltage with the primary leg voltage which is the voltage of the primary windings of any one of the transformers making the three-phase combination. Upon closing the switch between the secondary and converter a small magnetizing current circulated in the converter winding and caused the transformer voltages to drop to their normal value, which means that the leg values of the primary corresponded with the line values in the usual relation.

Sketch J shows a combination used for long distance transmission of power. Any triple-frequency component in the generator voltage simply results in shifting the neutral of the generator in case the neutral is not grounded and in rocking the three-phase voltage impressed on the transformer in case the neutral is grounded. Its effect, except for this rocking back and forth of the voltage triangle, when the neutral of the generator is grounded, does not appear anywhere in the line. The question arises as to why, if we find a considerable voltage between open corners of the step-down delta, a current would not flow in the delta when it is closed, corresponding to the voltage observed divided by the triple frequency impedance of the transformers? It was seen in Sketch I that under a similar relation of primary and secondary windings we observed nearly full-load current circulated. In Sketch J the triple-frequency voltage found between points of the open corner is due to the nature of the transformer, and therefore, only a very small magnetizing current is necessary to re-adjust the voltages. The current is inappreciable whether the neutral points are connected together or not.

Sketch K shows a combination of three single-phase station transformers for distributing purposes. The connection is $Y-Y$, and while not a common one, is used in at least two large cities in the United States, with this difference, that in one, both the high tension and low tension neutrals are grounded, while in the other only the low tension neutral is used for a fourth wire service. In the instance where the high tension neutral was not used, considerable trouble was experienced in the unbalancing of the phase voltages of the distributing system. If the load is perfectly balanced and the transformers used in the station have identically the same magnetizing current, then there would be no unbalancing of distributing voltage. However,

experience has shown that it is practically impossible to obtain such perfect conditions and therefore this combination is bound to result in extreme unbalancing of voltages.

In order to understand why this combination is so easily unbalanced it will be assumed that current is being drawn between the fourth wire 0 and the point C, Sketch K. This current represents unbalancing and is drawn from the winding $O\ C$ of the secondary of a single-phase transformer in a three-phase combination. But there cannot be current in the secondary without corresponding current in the primary. Thus, in addition to passing through $O\ C$ in the primary, the current must also pass through either $O\ A$ or $O\ B$ or both. No current is passing through $O\ A$ or $O\ B$ of the secondary. Therefore, any current passing through $O\ A$ or $O\ B$ of the primary must be magnetizing current. Thus, with very small current delivered between O and C of the secondary, the voltage between O and C of both the primary and secondary becomes approximately zero and the point O extends to C.

The unbalancing of the voltages was eliminated by connecting a three-phase transformer across the distributing lines in such a way as to admit the circulation of the balancing current.

Discussion on "The Regulation of Distributing Transformers", "Temperature Gradient in Oil Immersed Transformers", "Dissipation of Heat from Self-Cooled, Oil Filled Transformer Tanks", "Problems in the Operation of Transformers", Pittsfield February 15, 1911.

W. S. Moody: I will not attempt to contribute to any of the discussion, but I wish to point out one idea that has been specially in my mind in connection with the papers that have been presented this afternoon. Most apparatus, whether electrical or otherwise, requires some arbitrary or empirical formula to be used in its design. Transformers, among electrical apparatus, are, I believe, as little subject to these " cut and try " methods as any other class of apparatus, except for two characteristics that have been brought to the front in the discussion this afternoon—*viz.*, the calculation of the dynamic forces that must be resisted, and the predetermination of temperature rise.

For the first, we now have in the formulae recently developed the means of knowing what these forces are, and with this knowledge, taking care of them is a relatively simple matter.

When sufficient mechanical support has not been furnished for transformer windings, it has been due to an under-estimate of what these forces are likely to be, rather than any special difficulty in providing proper supports when the actual force to be encountered is known.

With reference to the second point—*viz.*, temperature rise, there has been a great lack of definite data. We can calculate a new transformer in nearly every other characteristic with great accuracy, but if the design is radically new, one could not, in the past, tell what the real capacity would be with a given temperature limit until tests were made.

Having determined the temperature by test, it is usually necessary to re-proportion the parts once or more to obtain the desired characteristics on the re-rated design.

To predetermine temperature rise one must consider a vast number of details, such as are considered in Mr. Weed's paper, and which have previously been neglected or allowed for in a very arbitrary way.

With such formulae as are discussed in Mr. Harper's paper, and such data and formulae as are considered in Mr. Weed's paper, I feel that there is no further excuse for the use of any " cut and try " methods being pursued in transformer design.

Henry Pikler: The papers we have just heard as some of the papers we heard earlier, interest probably the designing engineer more than the operator, since after all the operating engineer is satisfied if the apparatus in service fulfills the requirements of guarantees attached to it.

As to the various papers, Mr. Allen's paper on the " Regulation of Distributing Transformers " is a very able and clear presenta-

tion of the relation between resistance and reactance in the regulation of the transformer. A great many examples have been worked out and various formulas given to calculate the regula-tion, but in general I dare say I do not find the broad point of view from which the influence of both the reactance and the resistance could be clearly pictured. The following may be a clearer and simpler presentation of the facts: The regulation depends upon the mutual relation between resistance and reactance in the transformers; at loads of unity power factor the regulation is approximately equal to the resistance drop, and at loads of zero per cent power factor, it is approximately equal to the reactance drop; at power factors between the two, the regulation will be found between these two figures that is the resistance drop and the reactance drop combined.

Towards the end of the paper a method is given whereby good regulation may be obtained in transformers intended to be used for three wire distribution, lighting transformers. At this point it may be said with probably greater simplicity: In small size lighting transformers the resistance is the predominant component of the impedance. In larger transformers the reactances is of larger amount. Therefore, when we want to connect various parts of the transformer windings into parallel, so as to obtain proper three wire distribution and at the same time best regulation, in small transformers equal resistances in large transformers equal reactances should be connected in parallel.

I consider one of the most interesting papers, presented to us, that by Mr. Green on "Problems in the Operation of Transformers". Anybody who has had a chance to install transformers, to observe them in operation and to note the various phenomena in connection with them will appreciate the complexity of these phenomena and the difficulty of their clear presentation.

One of the most frequent sources of troubles in connection with transformers is their installation. At this point I wish to call attention to the fact that while almost always the transformer is tested at the factory of the manufacturer, in the presence of a representative of the customer, afterwards the transformer is installed frequently by the customer himself. The transformer is often found satisfactory in every respect at the factory, yet, at its installation breakdowns are not infrequent. Causes of this may be various and I shall refer to them later on, but I desire to use this occasion for suggesting the adoption of some rules, if that is at all possible, whereby the customer be held responsible for injuries to the transformer when he does the installation after having tested and accepted the transformer at the factory. The manufacturer should be held responsible only when his representative does the installation.

The causes of the breakdowns in transformers may be divided into two great classes. (1) Internal causes in the transformer itself. (2) External causes.

1. As to the internal causes I believe that defects in design, electrical construction, insulation, will show up at the factory if the apparatus be tested rigidly. At the same time there may be defects in the manufacturing which develop a weakness in the transformers only after it has been installed and operated for some time. At the present time the use of solid compounds for impregnation of the windings is almost universally adopted. The solid compound marks a great improvement in the modern transformer because it makes those mechanically weak coils of which we heard so much this afternoon, stronger by cementing together the turns and the insulation between turns and layers in the winding. At the same time the application of this solid compound is not so easy as it may look at first glance. If not done properly there may be found bare spots in the winding which have not been reached by the compound. At such places the mechanical wear and the dielectric stresses combined may create injurious effects in the course of time.

Also improper drying out before installation may be the cause of a breakdown.

One very good point brought out in this paper which I believe hits the nail on the head as regards internal causes, is the suggestion that the electrostatic capacity of the parts of the transformer should be small.

It is very interesting to follow the history of the design of transformers and of the means suggested for their protection. Years ago we heard that the weakest element in a transformer were the first turns and they ought to be protected most carefully by insulating them more than other parts, it was earnestly recommended to put a choke coil in series with the transformer or use the choke coil internally or even to develop the first few turns as a choke coil. *Now* we hear that it isn't so much between the first turns where the breakdowns occur but between other turns or parts of one winding. It would be very interesting to take oscillograms for the purpose of obtaining the voltage distribution between the various parts of the transformer winding under various conditions as switching surges, etc.

Again in this paper we find reference to forces in transformers arising on short circuits; it is suggested that the transformer be designed with sufficiently high reactance in order to reduce the short circuit currents, and the resulting forces. At this occasion I wish to say that contrary to the statements made by previous speakers that the low regulation of the transformer is chiefly due to the customer's demands for such, my findings are different: Low regulation is a natural sequence in transformers of large sizes; with the generally adopted principles of design and the economic utilization of materials, we cannot help but obtain a decreasing reactance with increasing output. Furthermore, we mustn't forget that it is not the per cent reactance that should be considered in this problem but it is the numerical value in ohms. To make a large transformer of high reactance is not

so simple as it may seem at first glance. A high reactance transformer means an expensive transformer. It means a transformer with many more ampere turns than in a low reactance transformer. More ampere turns means more copper and copper is an expensive material; besides copper requires winding space, hence a bigger iron core, in other words a larger and a more expensive transformer. On the other hand, if the high reactance be created by increasing the space between primary and secondary windings, we again get a larger winding space and larger core; in addition a tremendous self inductive field will be developed between these windings which is conducive to high eddy currents, heating and a reduced efficiency.

2. As to the external causes of breakdowns I wish to emphasize very strongly that in this respect the entire power system must be considered from the prime mover to the distributing apparatus. Concentrated condensers in parallel with the transformer created by neglect of grounding supports of high tension wiring, switching apparatus, etc., can pile up tremendous voltages on the system which may find an outlet into the transformer. Analogously concentrated choke coils may also be detrimental in the case of great variations in currents. Defective governors of prime movers, variations in speed and voltage, high winds which bring line wires on poorly constructed transmission systems in oscillation, improperly installed protective apparatus, surges of all kinds in connection with concentrated condensers as described above are the most frequent sources of breakdowns of transformers. Therefore before installing a transformer particularly on a high voltage long distance transmission system everything ought to be reviewed from the point of generation of the energy to the point of distribution.

As to the paper on " Dissipation of heat from self cooled oil filled transformer tanks ", again I do not find that broadness I looked for on this subject; although I must say that the paper presented by Messrs. Frank and Stevens is very valuable particularly for the many tests and numerical results given: In self-cooling transformers we find a great disadvantage results from the fact that the surface of the tank is not uniformly efficient. The useful surface is almost entirely the upper one; the lower portion depending of course on the proportions of the tank, is quite useless. Before we start to adopt various artificial means for increasing the radiating surface of the tank, we should first take advantage of the surface we already have, that is, make it as nearly uniform in efficiency as possible. There is one transformer tank that meets this requirement, this is the one with the external return pipe connections between top and bottom. This tank does not represent a novel idea; about eight years ago the Stanley Electric and Manufacturing Company—Mr. Chesney who is present will probably remember—had some transformer tanks in the shop of exactly that type, this type of tank was abandoned, however, on account of the excessive cost,

and the difficulty at that time in making the welding between the coil and the tank.

In comparison with the European practice it ought to be pointed out that European transformer designers and makers are far ahead in making self-cooling transformers and tanks, and it is not unusual that capacities as high as 3,000 kw., or over are made for self-cooling purposes. One reason for this may be that the European standard for the rise of temperature is 20 to 25 degrees higher than the American standard. I personally think that our temperature limitations are too low, particularly in view of the great improvements made in insulating materials during recent years. I think it would be absolutely safe to allow a temperature rise even as high as 60 degrees instead of 40 degrees, even in the over-heated power station.

E. G. Reed: Mr. Pikler has just made the statement that the European practice in regard to self-cooling transformers is superior to that in this country, referring to the size of units which can be cooled in this manner. The above statement should not be permitted to go unchallenged, as we are to-day successfully building in this country, transformers of this type up to as high as 3000 kv-a. capacity. The method of cooling employed is to provide oil tubes external to the transformer case through which the hot oil flows, being cooled in passing. This is a distinct advance in the art of transformer design. Such self-cooled units find their use, for example, in isolated substations where water for cooling is very difficult to secure and where it is desirable to dispense with an attendant.

Just a word in regard to Mr. Allen's paper: It seems to me that the most important point in this paper is the suggestion of the standardization in the method of calculating regulation on the basis of not taking into account the exciting current. If this method is correct, and I think it is, as it lines up with the Institutes' definition of regulation it should be generally adopted.

Louis F. Blume: Before regulation was defined by the American Institute of Electrical Engineers, it was proper to include exciting current in its calculation for transformers, because then by regulation, was understood the total drop at full load in the transformer from primary applied to secondary terminal voltage. When the Institute defined regulation as the difference between no load and full load primary voltage the consideration of exciting current became negligible. Thus, as Mr. Allen points out, the only influence of exciting current upon regulation lies in the fact that at no load it is greater than at full load. This difference, however, being so very small, is only of theoretical interest.

E. A. Wagner: The paper by Mr. Allen is typical in showing that the transformer engineer does do things accurately. Our worthy President intimated that transformer engineers did not get very close in their calculations, but rather guessed at them. Mr. Allen shows several formulae for the calculation of regula-

tion, and in these several formulae he works out to hundredths of one per cent. I think it is a matter of choice, no matter which formula you take, and I know that there is considerable discussion at times as to the method of calculating the regulation and working it down to very fine quantities, and I believe it is within the province of the Institute to make a recommendation as to some definite formula, so that in the case of a discussion between a consulting engineer and a manufacturer as to the method of calculating the regulation, there is something to refer back to.

It may be true that the formulae would be subject to such discrepancies as stray exciting current or magnetizing current might produce—you might want to segregate them—but I do not think that has any direct bearing on the matter, and I want to make a recommendation that this matter of having some recommended formulae for calculating regulation be taken up by the Standardization Committee.

In regard to Dr. Steinmetz's paper, which I did not discuss previously, would state that I had occasion a number of years ago to see an actual demonstration of the forces or stresses which followed from a short circuit. It happened at Niagara Falls, and was a case of 200 kw. transformer subjected to short circuit, and it showed that the busbar winding, which was about one-half in. by two in. was strained and actually forced and distorted out of place, and at the same time, due to the same causes, the cables in the alley running from the power house were thrown off the rack—that was an actual demonstration and showed at that time that these stresses did take place.

In regard to the paper by Messrs. Frank and Stephens, on the dissipation of heat from self-cooled oil-filled transformer tanks, my experience is in accordance with theirs. I think you will obtain about 50 per cent, make the figure a constant of 50 per cent, less watts per square inch, with a corrugated sheet steel tank than with a plain cast iron tank, and I have tried to follow that out carefully, and find that the practice agrees very closely with their curves. I think that the tendency to run to very deep narrow slots will give us dead air pockets, and believe the best results will be obtained by slots or corrugations having ratios of a depth not more than twice the opening. I have not made any attempt to calculate this and arrive at a mathematical conclusion, but as a matter of practice find that the above general rule gives the best results. I do not think that good results will be obtained from the boiler tube tank, because I have tried schemes of pumping hot oil into the bottom of the tank, and *vice versa*, taking cold oil from the bottom, and circulating it from the top, so that the surface of the tank reaches the same temperature throughout—under these conditions, the lowering of temperature with a transformer having a 40 degree rise without the circulation, my tests showed we gained one or two degrees lower rise which is not enough to warrant the additional complications which this system involves.

C. A. Adams: Referring to sketch H of Mr. Green's paper, it may be of interest to show why there must be a 3rd harmonic in the transformer flux and induced e.m.f., with three-wire star connected primaries, and secondaries on open circuit.

It has often been shown that a sinusoidal flux in a closed iron magnetic circuit such as that of the ordinary transformer, requires a magnetizing current with a considerable 3rd and a lesser fifth harmonic. But a third harmonic current cannot flow in a three-wire, three-phase, star connected system, since the third harmonics in the three wires are in phase when counted positive in the same direction along the line, and would therefore be all flowing towards the star neutral at the same instant, which is obviously impossible without a neutral return wire.

Assume the secondaries on open circuit, and neglect the fifth and any higher harmonics. The currents in the three trans-

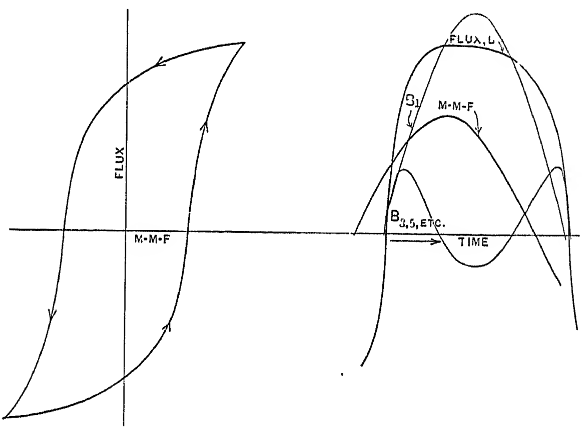


FIG. 1

former primaries will then be sinusoidal. Neglecting eddy currents, the relation between the m.m.f. and the flux is given by the hysteresis loop of Fig. 1. The sinusoidal magnetizing current or m.m.f. is plotted against time in Fig. 1. In both curves, time is indicated by the arrow-heads. The flux-time curve, derived in an obvious manner from the hysteresis loop and the m.m.f. time curve, is curve B of Fig. 1. The fundamental of the flux curve is shown in curve B, and the residual or higher harmonics in curve $B_{3,\,5,\,\mathrm{etc.}}$ From this it is clear that there is very prominent third harmonic in the flux curve, which increases with the maximum density.

Thus on open secondary circuit, there is a pronounced third harmonic in the flux and therefore in the primary and secondary e.m.fs. It is obvious that these third harmonic e.m.fs. in the primary phase or star e.m.fs., do not affect the line e.m.f., the

wave-shape of which is determined by the supply alternator. (The two third harmonic e.m.fs. connected in series between any two primary lines are 60 degrees apart in fundamental degrees, when counted positive from line to line through the star neutral, and therefore 180 degrees apart in third harmonic degrees. They thus neutralize each other and do not appear in the line e.m.f., but merely cause a rotation of the star neutral point).

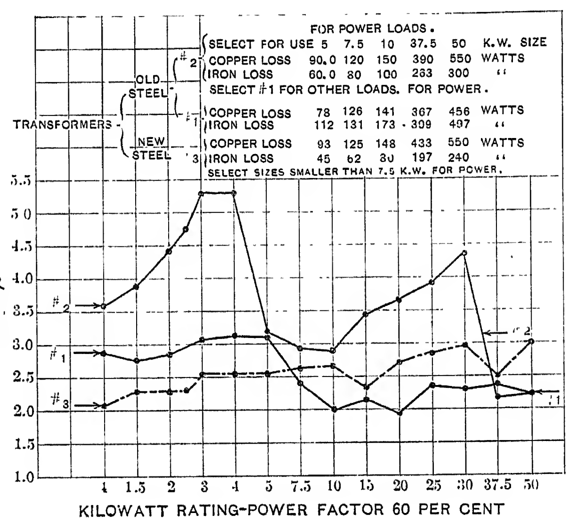
If now the secondaries be closed, either in simple delta or diametrally to a six-phase converter as indicated in Mr. Green's sketch H, the third harmonic, unless exactly neutralized by some third harmonic dynamic e.m.fs. in the converter, will produce third harmonic currents in the secondaries, the m.m.f. of which will tend to oppose their cause, namely the third harmonic fluxes in the transformer cores, *i.e.*, these third harmonic currents in the secondaries will act as exciting currents, will tend to supply the primary deficiency in this respect, and to restore the flux to the sinusoidal form. This restoration will obviously take place up to the point where the third harmonic secondary e.m.fs. are just sufficient to drive the necessary third harmonic exciting currents through the local (internal or leakage) impedances of the secondaries, and of the converter. As these third harmonic e.m.fs. are very small, the flux will be practically sinusoidal when the secondaries are connected as in sketch H.

It has often been stated that the design of electrical machinery is an *art* rather than a *science*, and while there was doubtless much of truth in the statement when it was made, the application of scientific methods to a rapidly increasing number of design problems is bringing about a condition not accurately described by the above mentioned statement. As one much interested in this particular evolution, I wish to congratulate Mr. Weed on his paper, which is a step in the right direction. Of all the problems connected with the design of electrical machinery, none is at present handled in a more crude and superficial manner than the very vital problem of temperature rise. To be sure, from the standpoint of scientific accuracy, the problem is hopelessly complex, but there is much room for improvement before we begin to approach that ideal, and every step means more rational and more economical designs.

A. E. Walden (by letter): Mr. C. E. Allen's paper on "The Regulation of Distributing Transformers" is very interesting, and is in line with the method the writer has been employing for over eight years for selecting transformers for power service. The small transformers were tested with actual load, both with lamps and choke coils, obtaining actual drop directly. The manufacturers' claimed regulation is shown in the chart for three types of transformers, two using the old iron or steel, and one the new steel, and the method of selecting to get the best regulation. Actual tests taken have given better regulation than claimed by most manufacturers.

Mr. Allen's paper does not bring out very clearly the resultant loss in feeders due to poor regulation, with consequent voltage and power increase at the generating station, and the increased power required at exciter, due to lower power factor in the motors or transforming devices. In the operation of generating station and the distribution system of to-day, considering the size, the condition of low power factor deserves more attention that it has heretofore been given.

In a large distribution system at low power factor, such as is usually found with induction motors, the feeder loss with an increased drop of three or four per cent in transformers will be found to be considerable in the aggregate. In a generating station of 8,000 h.p., which the writer inspected recently, the power factor was below 70 per cent during the day, due to the



fact that the load was nearly all motors. This will increase this loss considerably over iron loss.

It should be noted, further, however, that the regulation of transformers tends to improve slightly with power factors below 60 per cent.

Will Mr. Allen kindly explain what the increases in cross-section of the cores would be, also increase in weight per cent, to improve the regulation to that shown by curve No. 1. Also approximately what would be the increase in transformer cost if this was done, or could be done without changing the number of turns of the copper?

Ralph D. Mershon: I am sorry I have not had an opportunity to study these papers. I am especially interested in the paper by Mr. Weed and in that by Messrs. Frank and Stephens,

not only in their bearing upon transformer design but also in connection with other engineering work where almost exactly similar problems arise relative to cooling. There does not seem to be much published data applying to this problem, and in some cases where I have required data I have been helped out by information furnished by some of my friends engaged in transformer design. But the information they could furnish was not nearly as comprehensive as would be generally desirable.

Figs. 5 and 7 of the paper by Messrs. Frank and Stephens show corrugations of such form that the section of the air space within the corrugation is greater than the corresponding oil space. I should like to ask the authors whether they have arrived at a method of determining the relation between these sections for the best result and if so what that method is.

There is another feature of the problem somewhat similar to that of the relation between the sections of the air and oil spaces in the corrugations. That is the best relation between the areas of tank surface exposed to air and oil respectively. Suppose we have a cast iron tank, for instance, having ribs on the inside and ribs on the outside. We may make the ribs on the inside and outside of different depths so that, within limits, we may vary the relation between the area of the tank in contact with the oil and the area in contact with the air. Now it would seem to me that the temperature drop to transfer a given amount of heat from the oil to a given area of tank surface would be less than that required to transfer the same amount of heat from the same area of tank surface to the air and that, therefore, less area would be required on the oil side than on the air side. It would be interesting if the authors could give us data bearing upon this point.

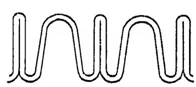


Fig. 1

It is not necessary to have a cast iron tank in order to control the ratio between the inside and outside areas. It can be done in a corrugated tank by collapsing some of the corrugations as in Fig. 1 and at the same time the relative sections of the spaces included in the corrugations can be controlled as indicated in the paper.

C. W. Stone: I have one or two questions in mind that I would like to ask—one is in relation to Mr. Allen' spaper. Fig. 9 shows a transformer which he calls a distributed shell type transformer, and Fig. 12 shows a core type of transformer. I do not see the difference. I wonder how he got at the name distributed shell type transformer. Apparently they are both core type. I think Mr. Allen could have brought out more prominently the increased cost of the transformer, and that bears out the point Dr. Steinmetz referred to, that the customer forces the price of the transformer down. If he has not done it, the manufacturers competing for the business have done it, which amounts to the same thing.

Mr. Pikler spoke of the breaking down of the transformer oc-

curring inside the transformer, in other places than the end turns, and he suggested this matter should be investigated. It has been investigated by the oscillograph with interesting results which will be brought out later in another paper.

I notice a point in Mr. Green's paper which I think is particularly interesting to all designing engineers as well as operating engineers, in referring to the percentage of puncture between high-tension and low-tension windings, or between the windings and laminations, as being negligible, as compared with the percentage of punctures between turns. That is based on years of experience after many investigations of burn-outs of transformers I do not think it is often given consideration.

Another point that Mr. Green makes is one that operating engineers overlook—they seem to think, if they put a lightning arrester on the line, they are free from trouble, and that if the transformer breaks down it is due to a defect in the transformer. I want to point out that the best type of lightning arrester that can be conceived will not protect the transformer, particularly if they are switched on the high-tension side. There will be internal surges which will break the transformers down, regardless of the lightning arrester. Put on all the lightning arresters you can get and then put on some more, and it will protect you from surges outside, but will not save the transformers. You must provide proper switch transformers, and particularly avoid switch transformers on the high-tension side or else you will have a breakdown.

Another point which Mr. Green makes is the question of external reactance. I am a great believer in external reactance. I am also a believer in internal reactance. I think it is a good thing to have, the more the better. I think as the systems grow larger and larger there is less need for what is called good regulation. The diversity factor which is coming into our central station work to-day means that our transformers are loaded a greater proportion of the time—consequently there is less need for the best regulation; on the other hand, as our diversity factor does come into the operation of our systems, our systems become larger and there is a greater need for reactance. Reactance in the transformer itself does a certain amount of good; reactance external to the transformer does still more good. I think that is also true in regard to generators. And I think it is a subject which should be considered in all large stations and provision should be made for the installation of external resistance, if not at the time of the installation of the transformers, at some later time.

I think there is something in Mr. Wilson's suggestion, and I would suggest that the Standards Committee take up the point, and that is the question of the temperature rise of transformers, particularly water-cooled transformers—should they be based on the air test, or should they be based on the water test. I think these two factors are important and should be considered, and they are not now considered in the Institute rules.

E. F. Alexanderson: In the design of any electric machine which is cooled by an effective system of forced ventilation the greatest problem is to predetermine the temperature gradient between the conductors and the ventilated surfaces. After the heat has been carried to a metal surface it can easily be carried off by the air. As an illustration, I wish to mention a convenient method to determine the heat radiation in machines cooled by air holes running crosswise through the laminations of the core. As result of test of various machines the watts per square inch radiated on the duct can be expressed:

$$\text{Watts per square inch} = 1 + \frac{\text{velocity of air}}{1000}$$

The velocity is expressed in ft. per min. based on 75 degrees rise of the conductors and a temperature rise of 35 degrees to 40 degrees including incoming and outgoing air. The formula is, of course, only a thumb rule, but I wish to point out the magnitude of the quantity. If the velocity of the air is 2000 ft. per min. the radiation is 3 watts per square inch or 10 to 20 times as great as the figures mentioned for exposed coils in transformer design. This indicates that the largest temperature drop is in the insulation.

There is another circumstance that points to some peculiarities of the heat conductivity of insulation. The behavior of some transformers indicate that the temperature rise of a ventilated coil increases faster than the watts per sq. in. In other words, the heat conductivity changes considerably with the temperature. In view of this the question would seem pertinent, what is the heat conductivity of the various insulating materials, and I believe it would be of benefit for machine design in general if rules for determining the heat conductivity of insulation materials received as much attention by the Institute as similar data for dielectric strength.

Henry A. Pikler: I want to refer, in a few words, to the remarks made by Mr. Stone—he pointed out two things, one is the switching of the transformers on the high tension line; he desires to have some method devised and adopted whereby this could be avoided; in other words, he wants to see some rules introduced and accepted by the customer or the operator that transformers should not be thrown directly in the high tension line; the other thing that he pointed out, is that the introduction of reactance outside or inside is desirable. It is very interesting to note how intimate the relations between these things are. As to the first point, I do not think that is feasible. I cannot imagine any way whereby we could avoid throwing the transformer on the high tension line directly, except by shutting down the power entirely, if this transformer be the first transformer at that point. If we insert reactances in the circuit—let us say,

more generally speaking, a series impedance, the result will be the distortion of the sine wave generated by the generator, at the terminals of the transformer.* This, of course, is quite serious, because we want to avoid the higher harmonics. With the introduction of the reactance, particularly at the moment of throwing on a transformer on the line, we will introduce these higher harmonics in a greater measure, than if we do not use the series reactance outside of the transformer circuit. And if the series reactance does not cause this then this proves its ineffectiveness for the purpose it was intended for.

C. P. Steinmetz: Regarding the remark made by Mr. Stone on the undesirability of high tension switching, I desire to endorse it, and still more particularly to draw attention to one interesting feature. We very often have done, and still occasionally do, things which we should not do, but we do them because we do not know any better, and as result, apparatus occasionally broken down by some mysterious phenomenon,

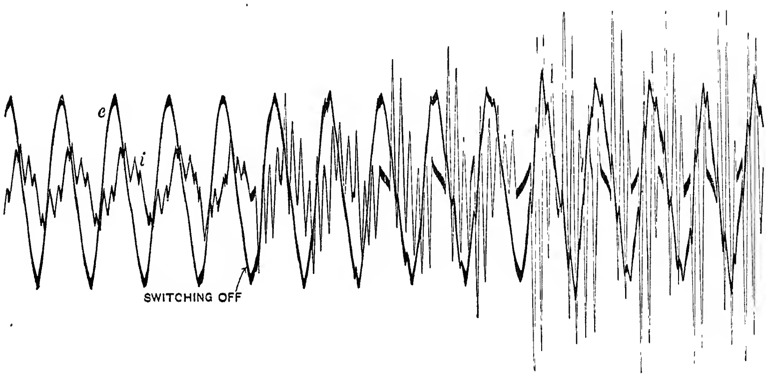


Fig. 1

which would not have been mysterious but for lack of knowledge. One of these things is the high tension switching. It has to be done, and will be done, but the less we do it the better it will be. We never realized this until we had the oscillograph on the high tension switch on very high voltage, long distance lines. It is easy to specify and say you must do it—certainly some time you may do it—but after looking at the oscillogram you will realize that the more we avoid high tension switching, the better it will be for the apparatus. In Fig. 1 is shown the oscillogram of a cumulative oscillation, resulting from high tension switching. Not shown in this oscillogram is the momentary and extremely local very high frequency traveling wave starting the oscillation, which is estimated of a frequency of two million cycles, and measured by its disruptive effects.

*H. A. Pikler, effect of series resistance in the primary circuit of a transformer. *Electrical World and Engineer*, 1903, p. 218.

Now, in regard to reactance, the place for high reactance is not in the high voltage line, where the high tension switch is objectionable. When you have a line in which you have to go to 100,000 volts, you are fairly certain there will be a voltage drop of ten per cent or more, whether the transformer has a high or low reactance, because the power which can flow through the transformer is limited. It is in those systems where the power is unlimited and the drop is negligible, a different class of systems, where the destructive effects of low reactance have been conspicuous.

When you speak of reactance, however, one thing must not be overlooked. If you say, a four or six per cent reactance is desirable for safety, that means you must have the reactance when you need it. It is wrong to put in an iron-clad reactive coil, which gives four per cent reactance at full load current, and when you get 25 times full load current, the reactance disappears by magnetic saturation, and wave shape distortion comes in. This has not been mentioned, because it is obvious. If you put reactance in to limit the short circuit current, the reactance must be there under short circuit, and this excludes the use of iron. In a transformer the maximum flux on short circuit is only full voltage flux, and magnetic saturation at short circuit thus cannot occur in a transformer, but in an additional reactance, it may, if iron is used, and that mistake has been made more than once, to use iron in power limiting reactances, with the obvious result, that the reactance was not there when you wanted it, and so did not serve the purpose for which it was designed.

J. M. Weed: Mr. Alexanderson's equation for cooling with forced circulation of air is represented by a straight line curve between watts and air velocity, cutting the axis for watts at one watt per sq. in. This line, no doubt, approximates the actual physical conditions for the high air velocities occurring in machines. For low velocities such as we find in the air which cools the self-cooled transformer the actual curve will be found to droop from the straight line and to cut the axis not far from the zero point. A similar condition exists with reference to the action of the oil in cooling transformer coils. This does not indicate that the largest temperature drop is in the insulation, as was suggested by Mr. Alexanderson, but rather that a very large temperature drop exists from the surface of the coil to the oil or from the surface of the tank to the air with the slow velocities occurring with natural circulation. This temperature drop at the surface is very much reduced by means of increased velocities obtained by artificial circulation. Some consideration was given to this matter in my paper and some also to the question of heat conductivity of insulating materials.

I would say that there must be something wrong with the transformer tests which showed a temperature rise increasing more rapidly than the watts per sq. in. producing this rise, since I have found from a large number of tests that there is a distinct

tendency in the other direction. I have not found any definite variation in the thermal resistance of solid insulating materials, but do find a reduction of the equivalent thermal resistance at the surface of the coil, or the tank, as the watts increase, which I have attributed to the increased velocity which is automatically produced in the cooling fluid.

Mr. Mershon's questions about corrugations, and relative areas of surfaces exposed to oil and air, are partially answered in the last few paragraphs of my paper. To be more explicit, without being too exact, I would say that the space on the air side of the corrugations may, to advantage, be made from two or three times as great as that on the oil side. The width of the oil space may be reduced to from one inch to one-half inch, depending upon the height of the tank, without causing a serious drop in the oil temperature while passing downward from the top to the bottom of the tank. The width of the air space should vary from one to two and one-half inches, depending upon the height of the tank and the depth of the corrugations. If this space is too large the heat does not sufficiently penetrate the enclosed air, and part of the space is wasted, while if it is too small the friction to the passage of the air is too great, and its acceleration is not sufficient to draw in enough new air to keep its temperature down to a point which is properly effective in absorbing heat from the surface of the tank.

Within limits the higher the tank the wider the corrugations should be, both inside and outside, and the deeper the corrugations the wider they should be.

It is instructive, when considering the size of the corrugations, to reflect that with a given ratio of pitch to depth of corrugation, and given perimeter, the area of the tank surface will be the same whatever the size of the corrugation. The volumes of air and oil brought within the corrugations, and thus brought within effective range of the surface, will depend however upon the size of the corrugations. If the reduction in size is carried to the limit, the conditions of cooling approach those of a plain surface, which gives the minimum cooling for the given perimeter, although we have not reduced the area of our corrugated surface. Thus, within limits, the larger the corrugations, the more effective the surface.

As to the relative amounts of surface which should be exposed to air and oil respectively, if there were just so much total surface which could be distributed at will between the oil and the air this question would be more logical. With the cast iron tank with ribs we can make either surface what we wish, regardless of the other. Though the ribs may be said to be less important on the side toward the oil than on the side toward the air, since the temperature drop from the tank to air is normally greater than that from the oil to the tank, yet they are valuable on both sides. Because we have ribs on the outside surface is no reason why we should not also have ribs on the inside surface.

With the corrugated surfaces, keeping the perimeter of the tank the same, the external surface will be increased somewhat by closing or collapsing the spaces on the oil side, keeping the width of external spaces the same, on account of the increased number of corrugations.

By closing all the internal spaces we might obtain an increase of about 50 per cent in external surface but this would be accompanied by a decrease of about 75 per cent in the internal surface. Assuming that the drop from the oil to the tank, before the corrugations are closed, is six deg., and that the drop from the tank to air is 30 deg., if each of these drops is proportional to the watts per sq. in. on the respective surfaces (which is not strictly correct) the respective drops after closing the corrugations will be 20 deg. external and 24 deg. internal. The sum of the two drops is now 44 deg. as compared with 36 deg. before the corrugations were closed. This calculation is rough and probably gives results somewhat exaggerated but it correctly illustrates the tendency.

Mr. Mershon may object that he did not contemplate closing all of the corrugations, but each corrugation must be considered to a certain extent independently, since the heat which would be conducted through the thin sheet steel tank from the corrugation which is not closed to the one which is closed would be much smaller than at first imagined. Moreover, the reduction in the temperature drop from the tank to the air will be less than would be expected from the amount of increase in the surface, since, not being adjacent to the hot oil, the tank temperature will be somewhat reduced toward the tips of the closed corrugation.

In addition to the above I should like also to offer some remarks on Mr. Pikler's discussion of Mr. Green's paper as follows:

Mr. Pickler's statements regarding mechanical forces and regulation in his discussion of Mr. Green's paper seemed to give a wrong impression. It is the natural tendency of the resistance element of regulation to be reduced with increased capacity, but not of the reactance element. Certainly the reactance in ohms would decrease but the per cent reactance, or reactance volts, tends to increase to the extent that for a given per cent reactance it becomes necessary to break the windings of a large transformer up into a larger number of groups than those of a small one. It is certainly true moreover, that the mechanical forces under short circuit conditions in any given transformer will be reduced by increasing its reactance. It is true, in fact, that if all dimensions and parts of the transformer including the coil supports are increased in equal proportion, all sizes of transformer will be equally safe, except for the affect of the variation in the space factor of the windings which is unfavorable for the larger sizes.

In order to be equally safe, therefore, the larger sizes must be protected by a greater than normal increase, either in the strength of the coil supports or else in the per cent reactance.

R. W. Atkinson (by letter): While the writer wishes to confirm certain of the points brought up by the author, he wishes to take exception to certain of the others. He is glad to see presented before the Institute, the formulae for the calculation of regulation and particularly those regarding the effect of magnetizing current, and would refer to the work done by the Bureau of Standards. The question was taken up very carefully by them, both theoretically and experimentally. They arrived at the same conclusions given by the author. Their results are published in their Bulletin No. 2, Vol. 6. However, the writer does not agree that the cost to the central station of regulation is ordinarily dependent upon the selling price of the power. He also wishes to comment slightly upon the curves in Figs. 4, 5 and 6. It is intended only to mention the above points with a very brief analysis of the reasons for the conclusions.

It is merely desired to call closer attention to the Figs. 4, 5 and 6. The casual reader might draw somewhat erroneous conclusions. In Fig. 5 it is desired to point out that with a purely lighting load where the effect of regulation is most marked, the influence of reactance upon regulation is least noticeable. It is suggested that the various transformers represented in Fig. 6 by curves 1 to 7, could scarcely be considered as having the same general dimensions. No. 7 would have $\frac{1}{4}$ the copper loss of No. 1. Obviously, this would require a very much larger and more expensive transformer unless, of course, some characteristics not mentioned are sacrificed. In case the reduction of the copper loss is at the expense of increased iron loss, the reactance would be reduced in approximately the same ratio as the copper loss. The same comment would apply to Fig. 4 but in a much less degree.

It has been frequently asserted that, on a lamp load, due to a reduction of voltage at the customer's outlet, regulation reduces the power sold to the customer and that therefore the cost to the central station is the difference between the selling price and cost price of this amount of power. Suppose this is true. We ask then why does it not pay to raise the voltage of the system and sell more power, why not do this indefinitely? It is unnecessary to analyze the reasons for not so doing. However, we know that it will pay to make the average voltage of the system approximately that which we would maintain all the time if it were not for regulation. If there is a certain voltage which it would be desirable to maintain uniformly, if possible, it would seem to scarcely require argument that if it is impossible to maintain a uniform voltage, the next best thing is to make the voltage vary *above* and *below* this desirable voltage, and as close to it as possible. The cost of regulation then lies in the effect of this variation of voltage, and regulation is costly just to the extent of the uncertainty and the variation of receiver voltage due to it.

An important effect of the irregularity of voltage is the re-

sultant variation of candle-power of the lamps of the system. In the case of carbon lamps, there is as well a variation of the color of the light. The problem then becomes quite largely one of the psychology of the customer. It is quite certain that if the variation of candle-power becomes serious enough to be offensive, it is very expensive to the lighting company, and is negligible only when not noticeable to the ordinary customer.

The most important effect of regulation is upon the life of the lamps. A lamp burning one-half the time at 109 volts and the other half of the time at 111 volts, has a shorter life than one burning steadily at 110 volts. It is possible to calculate this loss of life due to regulation very accurately from the performance curves furnished by the lamp companies. One thing of interest is that the loss of life varies approximately as the square of the regulation.

The average candle-power and efficiency are not so greatly affected. As a matter of fact, both are slightly increased under the above specific conditions of 109 volts half the time and 111 half the time, as compared with a uniform voltage of 110.

The copper loss of the transformer is so closely related to its regulation on a lighting load, that we may be pardoned for a brief reference to the cost of this copper loss. It needs merely to be mentioned that the cost of power occurring almost entirely at or near the peak, is much greater than the cost per kilowatt hour of an all day load. If this cost is the one cent per kw. hr., mentioned then perhaps the copper loss costs two cents. It is not intended here to show the amount of the difference but merely to call attention to its existence.

There are a great many factors which may influence this problem including those mentioned by the author. Some others are: regulation of the secondary circuit between the transformer and the customer's outlet; the possibility of the voltage of the primary being raised at times of general heavy load on the feeder. The first may be of considerable importance and complicate the problem accordingly. It is sometimes practicable to reduce materially the effects of bad regulation by consideration of the latter.

The writer has attempted to show in a general way that the cost to the central station of regulation is affected not by the selling price of the power, but by the effect upon the life and the candle-power of the lamp and upon the resulting satisfaction of the customer. Where regulation is important, that part due to reactance can always be kept low with less expense than that part due to resistance. The problem of the cost of regulation is an important part of the larger one, that of the cost of the transformer losses, and is a subject which is of great interest to both the designing engineer and to the operating engineer.

C. E. Allen: In regard to Mr. Walden's question regarding the increase in cross section of the cores, it is not clear as to just which figure is referred to, but at any rate the cross section of the core would vary, depending upon its construction. This

would be also true of the weight. As to the increase in cost of the transformer I have no figures at hand that are sufficiently accurate to answer this question, but I might add that the weight of copper would increase directly as the increase in the mean length of turn due to the larger cross section, and there would be also an increase in the weight of the copper due to the increase of $\frac{A}{L,}$ which represents the leakage path of the flux, in determining the regulation. It would not be an economical design to improve the regulation by increasing the cross section and allowing the number of turns to remain the same.

In replying to Mr. R. W. Atkinson's discussion, the writer appreciates that there is nothing original brought out in the paper, as all the formulæ brought in have been worked out by Dr. Bedell of Cornell University, Mr. Fortesque and various others. The writer has simply made a summation of correlated facts, with a view of showing certain points, which he hoped would be sufficient to justify the Institute adopting a standard method for determining the regulation.

As to the conclusions that might be drawn from Figs. 4, 5 and 6, this depends altogether upon the experience of the reader. The paper is only intended for those familiar with the subject. As to the variation in the power delivered due to changes in regulation, I have been over this subject with various central station engineers, whom I believe represent the leading men in their respective lines, and in all cases they have figured the loss due to poor regulation at the selling price less the cost of delivering the energy to the transformers. Mr. Atkinson asks why it would not pay to increase the voltage indefinitely. While this is no doubt obvious to many, I will answer by stating that there is the question of satisfactory service, which must be considered. Mr. Atkinson has based his statements entirely upon the assumption that only an incandescent lamp load was used. As a matter of fact the importance of the paper at this time is due to the increased day load made up of heating apparatus, etc., the nature of which is similar to that of an incandescent lamp, but where the question of renewals does not enter. On account of this increasing day load, the regulation and copper loss have both become of more importance than previously. At one time the iron loss of a transformer was considered to have a relative value six times that of the copper. This was assuming that full load existed only four hours of the day. To-day the same difference does not exist and, therefore, the value of the regulation and copper loss have been increased.

In taking up this subject the author has not dealt with its influence on induction motors; which is quite as important as the other loads. This is appreciated by central stations serving industrial districts and is brought out in Mr. A. E. Walden's discussion.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

OIL CIRCUIT BREAKERS

BY E. B. MERRIAM

Introduction. The problem of interrupting an electrical circuit which may be momentarily carrying millions of kilowatts is exceedingly difficult. The greater concentration of power at present under way and the obstacles to be overcome in controlling the huge electrical circuits of these developments are matters which were foreseen by the manufacturers, who keenly appreciative of the importance of these problems, are making earnest efforts to meet the conditions imposed. Unfortunately, it is inconvenient and at times even hazardous to make tests determining the ultimate rupturing capacity of heavy-duty oil circuit breakers, since these tests require the use of the largest power plants now in existence and those responsible for these power developments are rarely willing to loan their equipment for such tests. On account of the variable conditions of service reports obtained are of limited value and manufacturers are forced to accept incomplete information on the action of oil circuit breakers under operating conditions. This state of affairs is greatly improved where the engineers of the large power companies coöperate with the designers and carefully record and freely interchange data relating to all unusual disturbances.

Development. From a small knife-blade switch (Fig. 1) placed in a can containing oil of unknown quality, we have seen the oil circuit breaker rapidly pass through various forms until we reach the present high-voltage, large-rupturing-capacity devices with high grade oil (Fig. 2). They are the result of a natural evolution based upon the conditions imposed by operating men,

and also the results of much experimental work on the part of the manufacturers.

Function. The oil circuit breaker interrupts an electrical circuit in oil without producing abnormal disturbances in that circuit, and also confines the destructive effects of the arc to a small volume, thereby preventing its spread to adjacent apparatus and enabling the oil circuit breaker to be safely placed in any convenient location on the switchboard or in the power station. Air-break circuit breakers, owing to the large vicious arcs which they produce, are unsuited for general alternating current circuit-breaking applications. Fig. 3 shows an arc drawn by one of these devices when opening a circuit carrying 800 amperes alternating current at 13,000 volts. This arc, one of many observed, was

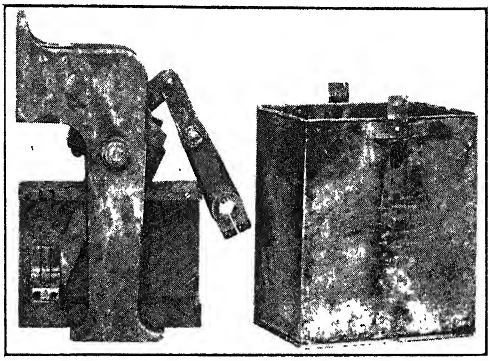


FIG. 1.—Early type of oil-break switch

about 180 in. (4.6 m.) long and rose 140 in. (3.5 m.) in the air, while the same circuit ruptured in oil produced an arc only 9 in. (22.8 cm.) long and with no external disturbance.

Action. A distinctive feature of the oil circuit breaker lies in the fact that when the alternating current which is maintaining an arc in the oil passes through zero, at which point the electromagnetic energy is a minimum, the current is interrupted and remains so until the voltage rises to a sufficient value to puncture the oil insulation which has been established between the contacts. As soon as this occurs, the current re-establishes itself and flows for another half cycle. This successive going out of the arc and re-establishing of it thus continues until sufficient insulation is interposed between the contacts to resist

the maximum voltage of the circuit, Fig. 4. The insulating layer of oil may be introduced by the rapid parting of the contacts, the confining of the oil to the immediate neighborhood of the disturbance, and utilizing the pressure developed by the arc, or the introduction of fresh oil under external pressure.

Application. While the duties of an oil circuit breaker are to connect, disconnect, and isolate different parts of an electrical system, its most important function is to relieve the system of dangerous overloads or short-circuits which would otherwise

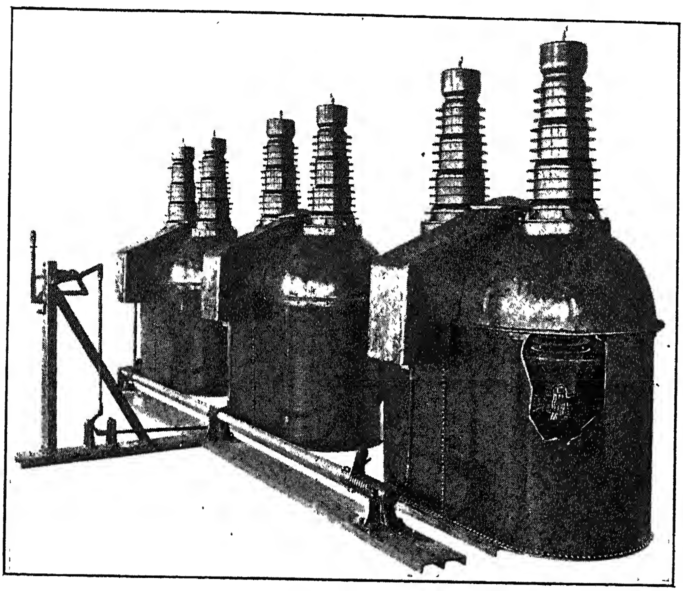


FIG. 2.—A modern high-voltage oil circuit breaker

prove disastrous to the service. The oil circuit breaker may act instantaneously or have its operation delayed by suitable time limiting devices. By these means, we are able to make them act selectively, and thereby isolate faulty generators, transformers or feeders without disturbing the supply of energy. From these various applications, oil circuit breakers take the names of generator, transformer, group, or feeder circuit breakers (Fig. 5). Generator circuit breakers are preferably *non-automatic*, as it would greatly disturb the system to have its service interrupted by generators continually disconnecting themselves. Trans-

former circuit breakers are usually equipped with overload, inverse time limit, or sometimes instantaneous differential relays, so that in event of trouble the faulty transformer will be isolated. Group circuit breakers may be set to operate after an abnormal

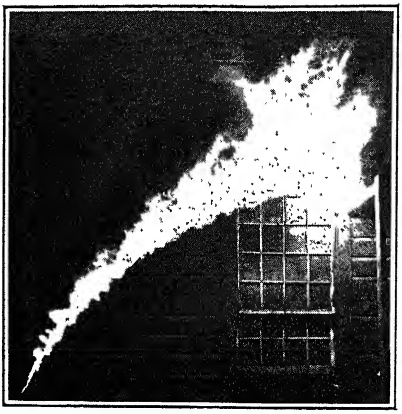


Fig. 3—Arc drawn by air-break disconnecting switch

condition has manifested itself for a certain *definite* predetermined time in order to protect the remainder of the system should the oil circuit breaker controlling the faulty feeder fail to operate. Feeder oil circuit breakers are generally equipped with an

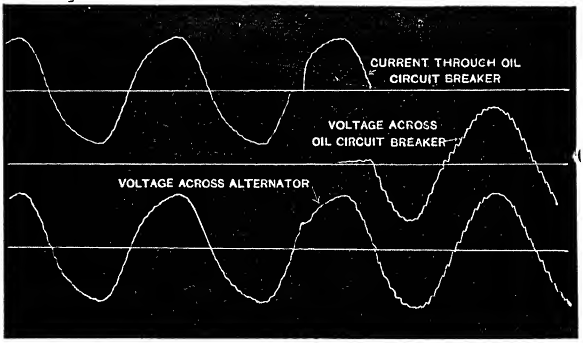


Fig. 4.—Oscillogram of an oil circuit breaker operating under test

inverse time element so that selective action may be secured in order to isolate faults.

Operation. The method of operating an oil circuit breaker whether by hand, electric motor, solenoid, or a pneumatic

mechanism, is largely a detail of construction, as any well designed circuit breaker may be interchangeably operated by any of these means, the circuit-rupturing feature being independent of the operating mechanism. For convenience, economy, and safety, large oil circuit breakers are remotely controlled so that they may be placed in fire resisting compartments very near the station bus bars. The control wiring should be installed in such a manner as to preclude its failure under *any conditions* as instances have occurred where circuit breakers have been the cause of the destruction of adjacent control wiring, thus rendering other circuit breakers inoperative.

Inspection and Oil. The severe service to which oil circuit

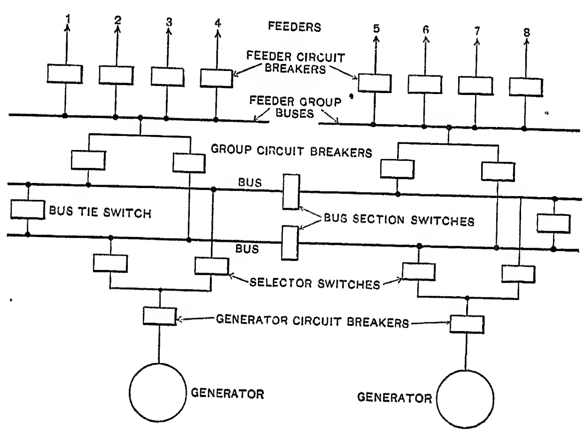


FIG. 5.—System of connections, showing location of oil switches and circuit breakers

breakers are subjected necessitates the regular inspection of oil, contacts and mechanism, with frequent attention to the general insulation. The oil may be carbonized considerably on a heavy short-circuit, and should inspection indicate this, fresh oil should be supplied. Carbonized oil may be filtered and the moisture removed, after which, it is again fit for use in oil circuit breakers. The quality of oil should also be given careful consideration. Its flash and burning points should be as high as possible—(not less than 180 deg. cent.)—as also its dielectric strength—(not less than 40,000 volts when measured between 0.5-in. (12.7 mm.) diameter disks placed 0.2 in. (5 mm.) apart)—to avoid leakage between contact sor from contacts to ground, and to increase it arc rupturing properties. It should be capable of extinguishing the

arc sprung by opening the switch and in doing this the carbon deposited should be a minimum. It should be free from acid, alkali, sulphur, or any other content likely to corrode the metal parts of the circuit breaker. It should be as fluid as consistent and remain fluid at low temperatures.

Insulation. The insulation of oil circuit breakers up to 60,000 volts is well taken care of by porcelain bushings and supports, but above this point, we have to resort to some other means. Here we begin to deal with very delicately balanced electrostatic forces whose peculiarities are only partially appreciated.

Time Factors. The total time interval between the instant

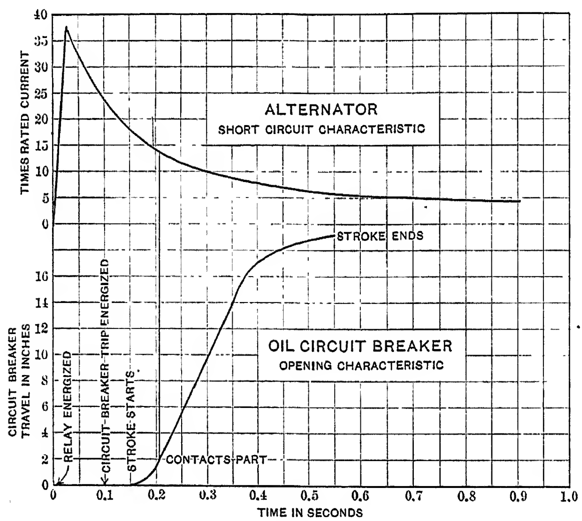


FIG. 6

the abnormal condition of a circuit is apparent and the instant the circuit breaker is completely opened, consists of the time element of the protective relay, and the time characteristic of the circuit breaker. The time element of the protective relay is the time lapse from the instant the abnormal condition of the circuit is apparent to the instant the circuit breaker trip is energized. It may be variable or constant, depending upon whether the timing feature of the relay is inverse or definite, or it may be entirely absent.

The time characteristic of a circuit breaker is the time lapse between the instant the circuit breaker trip is energized and the

instant the circuit breaker is completely opened (Fig. 6). This is influenced by the time which elapses from the instant the tripping mechanism is energized until the arcing contacts part, and the velocity with which this parting occurs. It should be remembered, however, that the arc is rarely, if ever, drawn the full travel of the arcing contacts of the circuit breaker.

Rupturing Capacity. The rupturing capacity of an oil circuit breaker is dependent upon a number of important elements such as the velocity with which the contacts part, their size and shape, the quality of oil, the electrical characteristics of the circuit, the direction, length and number of breaks, and the type of arc smothering device employed.

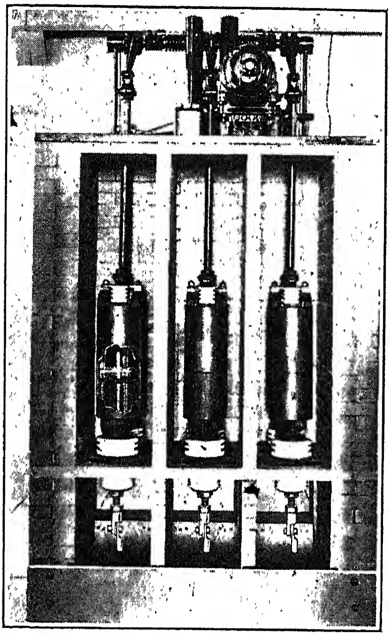


FIG. 7.—Modern high capacity, moderate voltage oil circuit breaker

When we consider the velocity of the moving contacts, we see that if they move apart slowly, the arc formed has time to become very violent and destructive, while, if we make this velocity sufficiently high, we reduce the time during which the arc can act, and thus diminish its effects, and increase the capacity of the oil circuit breaker.

The power-factor of the circuit to be opened greatly affects the rupturing capacity of an oil circuit breaker. If the power-factor is less than unity, the voltage is not in phase with the current and this permits the arc to be continued for a longer period.

The amount of current also affects the rupturing capacity of an oil circuit breaker, since upon its magnitude depends the destructive effects of the arc. Hence, anything which will reduce the current will diminish the work of the circuit breaker.

Another feature which we have to consider as affecting the rupturing capacity is the arc smothering device employed. A number of these have been proposed and some are now being

utilized, such as baffle plates, (Fig. 7) directed oil jets, oil pressure systems, etc., and it is due to their efficiency that we are enabled to control high capacity circuits and reduce the amount of oil required in oil circuit breakers.

The characteristics of an abnormal load such as a short-circuit, from which condition the oil circuit breaker is relied upon to relieve the system without interfering with the operation of synchronous apparatus or the interruption of the supply of energy, depends in a great measure upon the size and number of generators actively connected to the system, their internal impedance, and the impedance of the circuits between the generators and the point at which the abnormal load occurs. The enormous currents which have been encountered have led to the consideration of placing external reactance in the loads of the generator units in order to limit the amount of current which may be taken from them on short circuit. The present tendency, is to design generators with large internal impedance, even at the expense of regulation, in order to limit the maximum instantaneous value of the short-circuit current. This will permit generators to be short-circuited without material injury to themselves and greatly diminish the amount of current which the oil circuit breaker is called upon to interrupt, and will thus permit the use of an oil circuit breaker upon a system of larger capacity than heretofore, besides protecting the generators from injury.

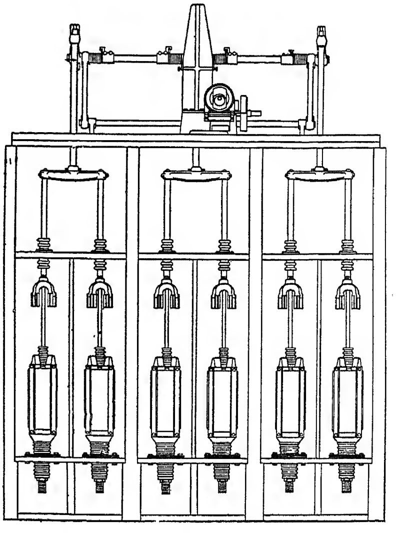


Fig. 8

DISCUSSION ON "OIL CIRCUIT BREAKERS". SCHENECTADY, FEBRUARY 16, 1911.

B. C. Jamieson: The subject of oil breakers is a very comprehensive one, and, as the title implies, all important is their efficacy as an energy rupturing device. Because of the extent to which they are used and the great amount of power behind them, moderate voltage breakers of high ampere capacity, such as are commonly employed on our large urban distribution system, are the most interesting.

Now with all the technique of operation aside, if the generally recognized limitations of this type of breaker could be removed, it will be conceded that the general switching and protective systems of large power stations would be simplified, and that expensive expedients, such as power limiting devices, would be necessary to a lesser extent. In other words, if it were possible to design a breaker which would instantly remove a member of the system, immediately it became faulty, without injury to the system, we would have the ideal breaker.

The outline of the basic principles, upon which the breakers described in the paper are designed, indicates that the development has been along entirely different lines. Referring to the curves given as the short circuit characteristics of an alternator and applying the switch operating principles, shown therewith, to a large system, consisting of five 14,000-kw. units, it will be seen that the operation of the breaker follows the period of maximum disturbance. The following questions naturally arise, what is to become, during this period of maximum disturbance, of our highly sensitive synchronous system of converters and the like? How much does the general structural reinforcement on the whole bus and switch system, under liability of this current necessary to safely carry these enormous current values, cost? How do we know that these characteristics apply at all when faulty insulation is the cause of the breakdown?

Attention is drawn to these points with a view of inducing the consideration by manufacturers of a type of automatic breaker which will prevent these abnormal current values. The value of such a device, combined with the absence of any assured limitation which might prohibit its development, amply warrants an effort in this direction.

E. M. Hewlett: The main point that does not seem to be appreciated by everybody is that with large generator capacity, switches must be designed to take care of whatever the bus bars will give them. Where the switches have a time limit, the time should be chosen so that you can get on the lower part of the curve shown by Mr. Merriam in Fig. 6, where the current rush is say three or four times the generator capacity. In that way you open the switch at a point where the current is limited.

If it is necessary to open the circuit instantaneously on very large powers, this can be done by making the switch large enough to do the work, but where economy of design in the station is required, you should put in a time limit, and also perhaps reactance, to bring down the work required to be done by the switch. In some cases, you can make the feeder switches smaller and have them take care of a certain amount of power by putting relays on them. This will permit the switch to open up to the power that it is able to operate under. Above this point, these relays will make the switch fail to operate and throw the work back on the main switch, when you can stand the interruption of service for a few moments on account of the economy of first cost of the station.

In reference to the rupturing capacity of switches, Mr. Merriam pointed out the baffle plate in Fig. 7. This baffle plate arrangement holds the oil over the contact and seems to be the simplest and most efficient way of keeping the oil there.

We have under consideration the making of a recording device for some of the large stations, so that we could get a record of short circuits in order to know really what occurs. We hear every once in a while that a switch has opened a very large amount of power successfully, and then we hear that a similar switch has failed on a comparatively small amount of power. There is too much personal element in these reports, so that we are laying out a device in order to learn the actual current conditions at short circuit. This, I think will help a great deal in our research work.

L. C. Nicholson: The principal lesson learned from extended experience in operating oil switches on high power circuits of medium voltage is that it is prejudicial to the successful operation of the switch to cause it to open several short circuits in a short time. Switches of approved type are apt to operate successfully once or sometimes twice within a few minutes, but damage to them will occur if they open severe short circuits in quick succession. This appears to be due to carbonization of the oil in the vicinity of the contacts, rendering the oil ineffective until the carbonized particles have time to settle to the bottom of the switch tank. This settling requires several hours.

As Mr. Merriam points out, a circuit breaker is favored if there is a time lag which prevents its opening on the first rush of excess current. We have found that a time limit of at least two seconds is required to insure the successful opening of a breaker under short circuit conditions.

W. L. R. Emmet: Many years ago I devoted a great deal of my time to oil switches and circuit breakers, but have not followed the subject very much lately, and I do not think I have much to communicate at the present time—the size of some of the circuit breakers recently built is very large, the designs being made to break the tremendous rushes of current which may occur on systems as now constituted; I think the circuit breakers have got about as large as they ought to be, and that further

avoidance of trouble should be accomplished by limiting the amount of current likely to go through any circuit, by the use of reactances and other means. This is now being done to a large extent, and I think that the growth of circuit breakers, as regards their size, will probably stop. These devices have been designed with a view to standing very high pressure and keeping the oil in contact with the break when it is possible to do so, but of course there are limits to this possibility and some of these devices which have been very strong, have been blown to atoms by some of the short circuits which have occurred. Many of the gentlemen in this room do not realize the extent and violence of some of the short circuits which have happened in different parts of this country. We had a short circuit in the Fiske Street Station in Chicago, in which the repulsion of the cables ripped many feet of clay ducts out of their masonry setting.

A Member: I would ask Mr. Merriam one point, about the necessity of inspecting the oil. He speaks of that point, and I would like to know just how much consequence that has proved to be in practice. That is to say, has it been found really necessary to test the oil periodically, and if so, what does that amount to? I should rather infer from the theory of the operation of the circuit breaker that the chances for carbonization of the oil are so small that the dielectric strength of the oil would decrease very slowly. I should like to know if Mr. Merriam can give any real facts on the point.

R. D. Mershon: I desire to ask of Mr. Merriam, what measurements, if any, have been taken, or experiments made, to find out the effect of temperature alone? I wonder in the case Mr. Nicholson spoke of, how much of the effect is due to temperature and how much to carbonization of the oil. In the case of some of the short circuits, I should think the oil would have a chance to get heated up pretty well, even with one opening of the switch.

C. J. Barrow: Mr. Merriam brings up in his paper the question of power factor, and states that with decreasing power factor the tax on the circuit breaker is very much increased. Yesterday we were talking pretty generally on the matter of placing reactances in bus bars and in generator leads, in order to limit the stresses in the generator and also the tax on the oil switch. It would seem, on looking into the oil switch phase of the matter, that putting a reactive coil in the circuit will not decrease the tax on the switch in proportion to the decrease in current effected.

In the first place the decreased power factor resulting causes for a given current ruptured an increased tax on the switch due to causes which obtain in any low power factor circuit—when the current reaches zero value and arc is interrupted the voltage at that instant available across switch break tending to maintain arc is greatest when power factor is a minimum. The tax is further increased due to the fact that a potential piles up across the reactive coils on short circuit, which when current is inter-

rupted appears across switch break and renders arc more persistent than is the case when generator terminals are short circuited direct. Considering the time-current characteristic of short circuit, Fig. 6, the effect of reactive coils will be to prolong the time required for current to reduce to normal short circuit value, so a switch with definite time lag will where reactive coils are used be called on to rupture a greater current value.

It should be noted in this connection that the falling away of current from a high value at the instant of short circuit to the normal short circuit value results of the "killing" of the generator field by short circuit currents in the armature. Until this "killing" process is complete the original field flux (built up before short circuit) is present in part, but bucked out of the armature windings by excess armature current, and a switch called on to rupture current under such conditions will be under a tax more than proportional to the current ruptured because when current is suppressed a voltage tending to reëstablish it becomes immediately available, the field flux now being free to take its normal path through armature windings. I think this point has a bearing on Mr. Hewlett's remark to the effect that a switch is at times greatly taxed by a system of relatively small kilowatt capacity and again on a larger system operates without evidence of tax.

In talking rupturing capacities it is customary to speak of the kilowatts ruptured as the product of the normal voltage of the circuit by the actual amperes ruptured. It seems to me that the instantaneous current ruptured by the voltage available to maintain it at instant of rupture is more to the point.

On the matter of insulation the insulation of any lead or terminal must provide against puncture and also against "flash-over", *i.e.*, passage of dynamic arc through air around insulation from conductor to ground. In low-tension apparatus the latter consideration is readily taken care of by simply providing an air path, conductor to ground, equal to or slightly in excess of the striking distance of test voltage which the lead must meet. In apparatus for service at 60,000 volts and upwards it is not so easily provided against and considerations looking to the control of "flashover" become the determining factors in the design of high-tension leads. The matter of providing sufficient insulation to resist puncture is in such apparatus a minor problem.

I wish to bring up for discussion the factors which enter to induce "flash-over". As is well known, an insulating surface will carry a charge. Considering a small area on the surface of a bushing it carries a charge just as would a piece of tin-foil placed over the area. The charge is determined by the location of the surface geometrically with respect to the insulated conductor and parts of ground potential. Likewise, another local area will carry a charge, the potential of which is determined by its position. An analysis will show that the difference of potential between these surface charges compared with the distance

of separation is greatest near base (flange) of lead. That is the surface potential gradient considering a path from the flange to the conductor over the surface of its lead is greatest at the flange. It is at this point that such a lead under potential gives first evidence of stress by corona, and later brush discharges and finally by sparking. The passage of a spark brings the points between which discharge takes place to a common potential and thereby increases the stress between these and surrounding points and so becomes progressive. It is a case of series breakdowns and its prevention a problem in potential distribution. The sparks are static discharges only. A spark lengthwise will induce transverse sparks and soon the whole base of lead is covered by a shower of static sparks, which practically "short circuit" the surface over which they strike. These sparks extend towards the conductor as the potential increases, presenting a path for dynamic arc—"flash-over"—at a much lower potential than would be required to produce flash-over in their absence. They are not the result of surface leakage, and are practically independent of the nature of the surface over which they discharge.

It has been the general practice to limit these discharges by interposing barriers (surface washers) in the path of the sparks Within limits this is a very successful expedient. In an ideal design the potential at any point on surface of a lead will be proportioned to its distance from the conductor and the flange. Approximating this condition in a practical way, desired surface potentials can be obtained by suitably proportioning the diameter of the lead throughout its length (when so proportioned resistance to puncture is amply provided for); or surface potentials can be determined by bringing to the surface at intervals ends of foils whose potentials are fixed by embedding in the insulating body concentric with the conductor. The final criterion of the efficiency of a design as regards "flash-over" is the relation which the striking distance of flash-over voltage bears to distance, conductor to flange over surface of lead. A lead having a 30 in. minimum air path, conductor to flange and showing a 300,000 volt test is evidently not handicapped by poor distribution of surface potentials.

H. W. Cheney: Mr. Merriam makes a general statement which I believe will be misleading to some in describing the action of oil circuit breakers. He infers that the current is always interrupted and reëstablished successively in drawing an alternating current arc in oil and that this action is continued until sufficient insulation is interposed between the contacts to resist the maximum voltage of the circuit. This action no doubt takes place when circuits of high potentials are broken on comparatively slow moving contacts. The oscillogram submitted by Mr. Merriam clearly shows that this action took place in the circuit breakers under test when the record was taken. In my opinion it is possible in a well designed circuit breaker to interrupt the circuit abruptly at the zero point of the current wave

without successive re-establishment of the current flow by means of rapidly moving multiple break contacts, especially on circuits of medium potentials. I submit herewith in support of this statement some oscillograms made during recent tests under my direction on a 200-ampere circuit breaker.

Fig. 1 shows an oscillogram taken at the point of current rupture on a circuit of 462 amperes, 2360 volts, 60 cycles. The

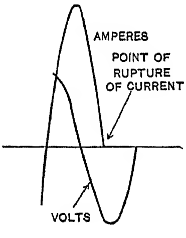


Fig. 1

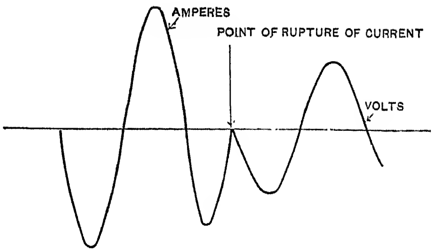


Fig. 2

voltage is connected across the line on the load side of the circuit breaker and the oscillogram clearly shows an abrupt interruption of both current and voltage waves.

Fig. 2 shows an oscillogram taken at the point of current rupture on a circuit of 384 amperes, 2400 volts, 60 cycles. The voltage is connected across the contacts of the switch, and the oscillogram shows an abrupt interruption of current wave at the

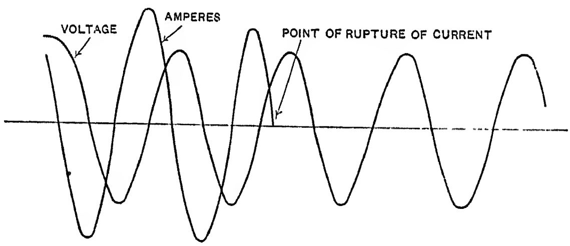


Fig. 3

zero point and also a simultaneous establishment of voltage between the contacts.

Fig. 3 shows an oscillogram taken at the point of current rupture on a circuit of 397 amperes, 2320 volts, 60 cycles. The voltage is connected on the generator side of the switch and the oscillogram shows an abrupt interruption of the current wave at the zero point. It also shows that the voltage wave is unaffected during rupture of the circuit.

The circuit breaker which was under test at the time these

records were made is provided with auxiliary arcing contacts which remain in contact until the moving element of the switch has attained considerable velocity. The moving element of the switch is comparatively light in weight and is spring accelerated at the point of contact separation so that a very quick break was obtained.

Mr. Merriam points out in his paper that high velocity of the breaking contacts is desirable, and I wish to say in support of this statement that my experience has shown that oil circuit breakers provided with multiple break contacts and high velocity moving elements at point of contact separation give the best results.

In many of the present forms of oil circuit breakers on the market the action in opening depends entirely upon the moving of rather cumbersome bodies through a comparatively heavy oil by means of gravity alone which results in very slow velocity at the point of contact separation, which is objectionable.

I would like to inquire the current, voltage, frequency and power factor of the circuit from which the oscillogram record illustrated in Mr. Merriam's paper was obtained.

A. S. McAllister: It is advantageous to limit the current on short circuit by means of reactance, yet it is undesirable for well-known reasons, to keep the reactance in circuit. Probably it would prove practicable to insert the reactance just when it is needed, leaving it out when it is not needed; in other words, to arrange the circuit breaker so that at the beginning of opening a reactance, on some such device, is inserted in the circuit to limit the current, and then the breaker opens the circuit only when carrying the lessened current.

Chas. F. Scott: We are having a demonstration of the universality of the laws of nature. Self preservation is the first law in apparatus as well as in animals. Yesterday in the consideration of transformers, nearly all the afternoon was spent, not in discussing the relation of the transformer to the power house, or to the consumer, and we were about to be discredited by having a long discussion on transformers without mention of hysteresis when Professor Adams came to the rescue and drew a hysteresis loop on the blackboard, but in discussing the self-preservation of the transformer to find what will keep it from burning up, or getting too hot, and what will keep it from distortion on short circuit.

In the paper on circuit breakers this morning, one of the most interesting curves shows the relation between the current in an alternator on short circuit and the time of opening the circuit breaker, and it was proposed that the circuit breaker wait a fraction of a second until the maximum trouble is over, and then come into action and do its part.

The question as to the time which should be allowed for a safety device to open the circuit is important not only from the standpoint of the circuit breaker, but from that of other apparatus. It may be noted that in Mr. Merriam's paper the

curve shows that in certain tests, the circuit breaker contacts parted one-fifth of a second after the relay was energized. If I recall Mr. Nicholson's statement correctly, he is endeavoring to get action within five cycles which is also one-fifth of a second, but he aims to have all operations completed within that interval, namely, only one-fifth of a second is to intervene from the time of the flashover, which may be 100 miles distance from the station, until the apparatus in the station comes into action and short-circuits a station of say 50,000 kw., and the short-circuit has been cleared and normal conditions have again been resumed. This interval is so infinitesimal that synchronous motors and rotary converters are undisturbed in their practical operation.

A general question which is raised is this—how far ahead should the designer look, in designing his apparatus? I mentioned the other evening some transformers which had operated for a number of years until the station was enlarged, and then the coils were found to distort. Mr. Emmet mentioned this morning certain switches which were believed to be perfectly satisfactory, because they operated well on some four or five large generators, but afterwards were found to be inadequate. Lightning arresters which were standard and operated satisfactorily for years were found inadequate when the capacity of power stations was increased. Now, when things are found inadequate, does it mean that the designs are defective and the designer is to be held accountable? Or is the fault due to something else? We certainly cannot look ahead, and be designing all our apparatus now for the time to which our president is looking forward, when the whole country will be interconnected with a 500,000 volt circuit, and practically unlimited energy will be available in each short circuit. It seems to me that the responsibility of the designer is to recognize what the actual specific conditions are, to properly adapt the different parts of the apparatus so as to operate successfully in the plant for which they are made, not necessarily in some other plant or some ultimate plant. He must understand the kind of conditions we have been considering here so that he can foresee and determine what the proper relation and strength of the different parts of the apparatus should be before they are installed, instead of learning them after trouble has occurred.

There is one other little interesting side note to which I desire to refer. The day before yesterday and to-day we have been treated to examples of the oscillograph. I believe all the papers at the Wednesday evening session, and the first paper this morning, are filled with oscillograms. Yesterday, in the papers on the transformer, the oscillograph was entirely neglected, until fortunately some one brought it in to save the day by referring to it incidentally in the discussion. The work of the oscillograph has given some new insight into these problems and makes their analysis a very different matter from what it was a number of years ago.

C. P. Steinmetz: The problem of the oil circuit breaker has always been and still is that of quick opening versus slow opening. If we can hold the contact closed until the generator field has gone down to its normal short circuit value, then we get the safest condition for the oil circuit breaker, but we do not put an oil circuit breaker in a system for the purpose of having the oil circuit breaker safe, but to save the system, and one of the reasons why we have the circuit breaker, is to protect the system from destruction by these enormous short circuit currents. That means that we must open the circuit breaker as quickly as possible to save the system. Where the short circuit current is limited by a long transmission line, so that its value can never be disastrous, then it is safe to hold on, but not otherwise. That means as quick opening as possible. There is a limit to that—it must not be overlooked that the circuit breaker is not there merely to open the circuit, but to open the circuit without causing any damage to the circuit, and if you open too quickly you get an oscillation—a good illustration is that of the condenser shunt in the Rhumkorff coil. Without it, the spark at the circuit breaker causes a slow opening, and you get a little bit of a thin spark, but with the condenser, you get a big spark in the Rhumkorff coil. That is the kind we do not want in our system. We get high voltages and other undesirable impulse forces more than we wish, and there is no need for creating them by abnormally quick opening of the circuit. Hence, we do not want a condenser which takes the momentary current rush away from the circuit breaker, storing it in the condenser, and then returning it into the system to add to the excessive power which at the same time is coming from the gnerator, and doubling up our strains by returning the stored energy into the system. We want a circuit breaker to open as quickly as possible to protect the system, but not quicker than it can open safely to the system, without producing disturbances in the system which may be dangerous.

H. L. Smith: There is one point that Mr. Merriam proposed in the paper, which is much condensed, and that is the question of the rating of oil switches, both for their heating limit and voltage tests. It seems to me it might be well within the scope of the Institute rules to take this matter under consideration.

One point which has been quite largely dwelt upon in connection with the rupturing capacity, which after all is one of the most important factors of the switch, is the question of power factor, and that is interesting from another point of view, although partially covered in Mr. Hewlett's remarks, and that is in different sizes of stations we may get different effects on the oil switches due to the variation of power factor—that is, it is conceivable that some of the smaller stations may give worse conditions than a station of 50 per cent larger capacity, and that, of course, introduces a problem that has to be considered in the selection of the oil switches. The question of rating these

switches has in the past been based almost entirely on the results of numerous tests, and presumably these tests have been made at relatively low power factors, consequently it appears that they are along the right line. I think that additional tests at much higher power factors may give us further information, which can be checked over and give us more complete and accurate data for future developments.

E. W. Rice, Jr.: I have not heard any reference to what seems to me to be a rather important factor—it has been stated that it is necessary to have the circuit open very suddenly. In modern central station practice reliability of service is paramount to all other factors. This means that everything is sacrificed to keep the current on the system. It is therefore desirable that the circuit breakers of the generators should be so arranged as to operate only after a considerable period of extreme overload or short circuit has existed. On the other hand, the feeder nearest to the short circuit should be arranged to open in a relatively short time.

It has been suggested, and I agree, that the proper method of operation is to arrange the system so that the current resulting from a short circuit will be automatically limited so that the flow of energy may be kept within a practicable amount. The permissible flow of energy will depend upon the character and size of the system. The best method of limiting this flow of energy in the case of a generator is to increase its internal reactance, but where this is impracticable, to insert additional external reactance in the generator leads. This reactance can be so adjusted as to limit the short circuit and bring it within the capacity of the circuit breaker. Similar external reactances can and should be inserted in important individual feeders so proportioned as to limit the flow of energy to the desired amount. If these reactances are properly designed and installed in a system the circuit breakers can then be provided with time limiting devices so adjusted as to maintain the current upon the system the maximum possible time. Naturally the generator circuit breakers will be adjusted to a longer period so as to open at a later time than the feeders, and as the outskirts of the circuit are reached the circuit breakers can be operated instantaneously as the amount of load which is then disconnected from the system is relatively small in proportion to the total load. Such methods are now being introduced in large alternating current central station practice, and the apparatus, generators, transformers and circuit breakers under such conditions must be made to successfully withstand whatever duty is placed upon them. By such means we can prevent the electrical apparatus from being destroyed and at the same time maintain the maximum continuity and reliability of service.

E. B. Merriam: Mr. Jamieson raises the point that a circuit breaker, in order to render proper protection, should open before the current in the circuit reaches its maximum value. In

a number of tests, it has been found that the rate at which the current increases on a dead short circuit is approximately 1,000,000 amperes per second, so that we can readily see the great difficulty presented in designing a circuit breaker to take care of this enormous current increment. The introduction of current-limiting reactances in series with the generator leads tends to limit the heavy current rushes which are present on short circuits and to lessen the strain on the bus and switch systems. This seems to be a much more effective method of protection than increasing the size of the circuit breaker to take care of abnormal conditions unaided.

Mr. Nicholson points out that in his experience successive operation is bad for circuit breakers. We find that the failure of oil circuit breakers after opening successive short circuits is due principally to the ignition of explosive mixtures which are formed from the gases generated by the arc combined with the air in the top of the oil vessel. The amount of these gases is dependent upon the volume of the arc and its duration and these in turn are dependent upon the current which the circuit breaker is interrupting together with the voltage across its contacts and the velocity with which the contacts part. This explosive mixture may be prevented from forming by replacing the air in the upper part of the oil vessel with an inert gas.

It has been our experience that the stresses in oil vessels rarely exceed 300 lb. per sq. in. In cases where cells have been disrupted as described by Mr. Emmet, this has been due not to the failure of the oil vessel but by the mechanical failure of the insulator in the top of the oil vessel. To our knowledge, the oil vessels have never been destroyed except from secondary causes.

The necessity for the frequent inspection of oil is more of mechanical than electrical importance and it is rather difficult to make a statement which will adequately cover all cases. Moisture affects the rupturing capacity considerably more than carbonization, while temperature effects are nullified after sufficient time lapses.

Mr. Barrow points out that the introduction of reactance coils into the circuit theoretically increases the tax on oil circuit breakers due to the lowering of the power factor of the circuit, the adding of the reactive kick to the circuit voltage and the retardation of current decay. However, it must be remembered that the introduction of these devices makes the short cir uit current very much smaller so that the ultimate result is to actually diminish the tax on the circuit breaker.

The rating of oil circuit breakers with respect to their rupturing capacity has always been open to more or less discussion and as Mr. Smith suggests, it may be within the scope oi the Standardization Committee of the Institute to consider this matter. However, in any case, it deserves careful study and all circuit breaking apparatus should be rated on a common basis.

Some comment has been made with respect to insulation.

On the lower voltages, this is very adequately taken care of by porcelain, but at voltages above 45,000, considerable experimental work will be necessary before satisfactory insulation is arrived at.

Mr. Cheney is quite right in stating that the current is not always interrupted and reëstablished successively in drawing an arc in oil. This action, however, is more apparent on high voltage circuits where the contacts move comparatively slowly. The oscillogram shown in Fig. 4 was taken on an oil circuit breaker when opening a circuit carrying 50 amperes at 6000 volts, 20 cycles, at unity power factor with the contacts moving apart at an average velocity of approximately 13 ft. per second.

Recent tests have shown that it is not undesirable to keep current limiting reactances in a circuit continuously since the loss which they impose is very small and the wave distortion slight.

Mr. Scott brings up the interesting point of how far ahead a designer should look in making up apparatus. Circuit breakers are built to take care of ordinary conditions and future additions to the generating equipment, when radically different, can either be taken care of by current limiting bus reactances or changing over the switching equipment.

Mr. Lichtenberg's comments in connection with the position of a circuit breaker relative to the generating station is worthy of consideration and in many cases, it is possible to use a comparatively small breaker on a large system if the location is sufficiently remote from the source of energy. Considerable information can be gained from the operation of oil circuit breakers considered as an energy dissipating device as pointed out by Mr. Lichtenberg.

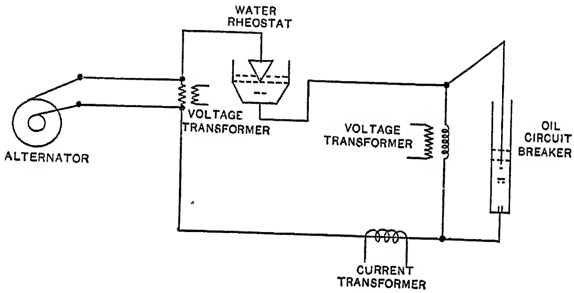
Mr. Collis points out that it is English practice not to have large generator capacities so connected as to permit heavy current rushes at short circuit. There are power houses in the United States, however, whose normal bus bar capacity is approximately 120,000 kw. and it is possible to concentrate the short circuit energy of this system on any one of a number of switches. A conservative estimate of the instantaneous energy available at point of current interruption is approximately 1,000,000 kw. The advisability of concentrating this amount of power is largely a question of the character of the system since the practice of the New York Edison Company is to operate all of its alternators in parallel while the Commonwealth Edison Company of Chicago prefers to group its generating units.

Current increments of 800,000 amperes per second are very common in the United States on short circuits and tests have recently been made where the current increment was approximately 1,500,000 amperes per second. Experiments have been made on switches opening a circuit within 0.01 second with very gratifying results but there has been no opportunity to place

these on large capacity systems. The oscillogram shown in Fig. 4 is representative of a number of tests and the accompanying sketch shows the diagram of connections for test during which this was taken. The system of connections shown in Fig. 5 is not intended to show the actual connections of any particular power house but merely to locate the various switches and circuit breakers in order to assist in the discussion of their various functions.

It has been American practice to advocate the use of non-automatic oil circuit breakers for use in generating units since it has been found that where otherwise equipped, they would continually disconnect themselves and seriously interfere with the continuity of service. However, in some cases the generators have been fitted with indicating reverse current relays with marked success.

The theoretical treatment of the transient phenomena during the operation of circuit breaking apparatus requires the consideration of a large number of independent variables. Such a



study is very difficult but important and deserves much attention.

Chester Lichtenberg (by letter): In discussing action, the author states that a distinctive feature of the oil immersed circuit breaker lies in the fact that when an alternating current which is maintaining an arc in oil passes through zero, the current is interrupted. There seems to be considerable difference of opinion among engineers concerning this point, but from numerous experiments which we have made, the conclusion has been reached that where the amount of energy is small, the voltage relatively low, and the current not too great, this type of circuit interrupting device may open the circuit at almost any point of the current wave. However, for voltages above 500, and currents in excess of about 200 amperes at commercial frequencies, it has been found that the current is invariably opened at the zero point of the wave. The author also points out that when the current is interrupted at the zero point, it remains so until the voltage rises to a sufficient value to puncture the oil

insulation which has been established between the contacts. This is absolutely true for certain conditions of voltage, current, and velocities with which the contacts part. However at power factors other than unity, it has been found that the persistence of the current tends to continue the arc, and prevent the interruption of the current at the end of each half cycle, although there is a tendency for this phenomenon to occur.

Under " Function ", the author states that an oil immersed circuit breaker should interrupt an electrical circuit without producing abnormal disturbances in that circuit. In addition to this very important function, the circuit interrupting device must assist in dissipating the stored electromagnetic energy of the system connected to it, and until this point is fully appreciated by designers and operators, the study of such devices will not advance beyond the primitive stage. This can be readily appreciated when we consider that any electrical circuit will have more or less inductance and capacity in addition to its resistance. Hence every electrical circuit will have more or less stored energy which must be dissipated when that circuit is interrupted. This dissipation takes place either at the point of interruption, or in the circuit itself, as a result of oscillations. When dissipated at the point of circuit interruption it is manifested principally as heat and chemical energy. Thus it may be seen that when systems are short circuited, and the circuit interrupting devices are opened and closed repeatedly upon this short circuit, the medium surrounding the contacts of these devices becomes heated. If this medium be oil, it is very likely that the flash point of the oil may soon be reached, and this will be followed by its ignition. This action will result in an increase of the internal stress in the oil vessels, and may result in an explosion if the device is operated while this condition exists.

In discussing time features, the author divides the total time interval between the instant the abnormal condition is apparent and the instant the circuit breaker is completely opened, into two parts. Most everyone who speaks and thinks of a circuit interrupting device, considers only the first portion of this interval. The second portion, that is, the time lapse from the instant the contacts part until the stroke ends, is equally important. Upon it depends the rapidity with which the circuit is opened. If this time is short, the arc produced is small. But if it is long, the arc is permitted to become very vicious, and may produce oscillations in the circuit. Again, if this time is too short, we will approach the condition of quickly interrupting a highly inductive direct-current circuit, and thus also set up destructive oscillations. Hence there seems to be a definite velocity with which the contacts part, resulting in a maximum efficiency for the circuit interrupting device.

Referring to power factor and its effect upon a circuit interrupting device, we must remember that power factor is really another way of stating the difference in phase that exists be-

tween the voltage and the current in an electrical circuit. In addition, however, the power factor indicates the amount of stored electromagnetic energy in the medium surrounding the circuit. Hence, it may readily be seen that when the power factor of the circuit is low, other conditions being equal, the duty of the oil immersed circuit interrupting device is considerably greater than when the power factor is unity. In the former case the stored energy which must be dissipated at the switch when the circuit is opened is considerably greater than in the latter case. In this connection it is well to remember that circuit interrupting devices when placed very near large capacity generating units, must perform much more severe service than when placed a considerable distance away (electrically) from these units. When near the generators, the circuit breaker is called upon to dissipate most of the stored energy of the system, while when remote from the generators, a considerable portion is dissipated in the electrical circuit as a result of oscillations.

A. G. Collis: I notice that the author refers to a circuit carrying momentarily "*millions*" of kilowatts. There is no circuit carrying this capacity in connection with any power station yet designed, and if such a circuit were designed, it would not be advisable to rely on the efficacy of one switch to rupture such a circuit.

The engineer who designed a power station where a switch would be called upon to rupture "*millions*" of kilowatts would be courting disaster. The largest power supply in this country is equal to 35,000 kw., subdivided into groups. Even supposing that a switch on the bus bar side had to interrupt the total power behind it, the maximum rupture in such a case would not exceed 150,000 kw. Then again, the rupture efficiency of the switch would depend on the position of the wave at the moment of opening. The quality possessed by turbo-generators as at present designed for large outputs, *viz.*: the standing up to its work, has been realized in this country. This quality greatly increases the effects of a short-circuit (at present, the generators are not designed with large internal impedance), and switches have been designed to open the circuit as rapidly as possible, as the current increment at the instant of opening may be at the rate of 800,000 amperes per sec. (apart from the fact that the rapid opening of circuit may lead to excessive pressure rises). If, however, the current can be disconnected before it reaches a dangerous value, the rise of pressure may not be excessive. I have designed a switch that will open a circuit under the conditions referred to, and entirely disconnect the supply in less time than one half of the periodic wave, and I have taken oscillograms which show this time element to be 0.01 of a second.

There is another design of switch that will dissipate the rising energy during this time so that abnormal stresses have not to be interrupted during the switching off. This switch is designed so as to completely open the circuit in 0.02 of a second. Oscillo-

grams have been taken showing the results obtained with these switches and in every case, on voltages reaching to a pressure of 25,000 volts, the current has been finally interrupted at the zero point, in the first half of the periodic wave of the circuit. Hence, I doubt the statement that current passes in several waves when switching off.

I give below, some information concerning the records of tests attached hereto, and I enclose diagram of connections, Fig. 10, showing how the oscillograph was connected up.

It is particularly interesting to notice that the potential coil of the oscillogram is connected across the contacts of the switch, and seeing that one side is earthed, the wave of the potential is between phase and earth.

With regard to the oil-switch illustrated in Fig. 2, the development of this form of switch in this country, originated from the water-break-switch, and it is still used in connection with oil switches for direct currents in gassy mines, the water acting non-inductively on the circuit.

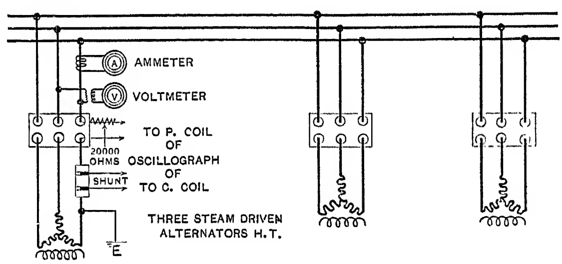


FIG. 10—Alternating current high-tension induction test

The air break switch as shown in Fig. 3 is also interesting, but the oscillograms in Fig. 4 cannot be interpreted as there is *no* diagram showing how the oscillograph was connected up. It is therefore impossible to discuss the relative points of this oscillogram. As a matter of fact, it would appear to be impossible to get a curve such as shown, correctly, unless the current curve is the capacity of the current of the inductive circuit. The potential coil of the oscillogram must be at earth potential, and it appears to me that there is a discrepancy in the relations of the potential and the current curves. In the potential curve there does not appear to be any induced e.m.f. and change of current. This may possibly be due to the fact that the circuit has no appreciable capacity. However, in the absence of information relating to these curves, they cannot be discussed.

With regard to the diagram of connections shown in Fig. 5, I do not think that any engineer in this country would consider such a scheme as referred to. Here, simplicity is of primary importance, and the duplicating of groups, as illustrated

would be considered a complication. I may say that grouping, at Cot's Road Station, in this country, led to disaster. The operator did not consider the numbers of the groups, and paralleled all sets of the power station right across the bars, with the result that when the current transformer grounded it short-circuited the switch contacts, which formed practically a short circuit across the whole supply and caused the power station to be shut down for a time.

I do not agree with the author that hand-operated switches should be used for generators, but I advocate reverse relays that will open under a variable power factor—on a small percentage of reverse energy or otherwise, I have used a balanced system of protection.

I notice that the author advocates overload and differential time limit relays for circuits, but it is very difficult to get a discrimination of time values when running on a long feeder so that a short circuit at the end of the feeder shall be relieved without interrupting the entire feeder. Discriminating and overload relays show very little difference in time values under a short circuit condition, and they all invariably come out together.

Regarding protection for transformers, again, overload relays are not considered to be good practice, and in this connection, the high- and low-tension side is interconnected so that should a short circuit or an overload occur in the transformer itself, the transformer will be isolated both on the high- and the low-tension side, simultaneously.

Fig. 6 is not clear to me in respect to the time rated current which is given between zero and 40. I do not know what this figure represents. Apparently the highest peak on this short circuit characteristic appears in less than 0.01 of a time, which, again, is impossible, assuming that the rise is a current rise. If my assumption is correct, it is demonstrated that the highest peak occurred before the circuit breaker trip was energized. Therefore, the system put forward in the diagram proves it to be incorrect.

From the accompanying oscillograms, you will notice that the switch I have designed will open and finally interrupt the circuit in less time, as plotted out in Fig. 6, *viz.*: the circuit breaker trip energized 0.1 of a circuit completes (in my case) interruption in 0.01 of a circuit.

I notice that the stroke of the switch ends in 0.55 of a circuit, which is a dangerously long value, and in fact too long for satisfactory work.

Fig. 7 shows a motor operated switch for the voltage of 60,000 volts. I prefer a solenoid-operated switch, which has a more positive action and is noted for its absence of complications.

With regard to switches for voltages higher than 60,000 volts, I have put forward pneumatic operated switches, so that instantaneous rupture can be effected quicker than by the gravity opening of a solenoid switch.

Alternating Current Tests

The alternating current tests made were of two kinds:

1. High-tension with inductive load.

High-Tension Tests

Arrangement. The arrangement of the high-tension tests is shown in Fig. 10.

The plant consisted of three steam sets driving alternating current three-phase 6500-volt generators of the rotating field type. The sets were first run up in parallel, after which the steam was cut off from two of them, the remaining set driving them as motors.

As it was necessary that the potential coil of the oscillograph should be grounded, one phase was grounded, the pressure consequently being reduced to about $\frac{6500}{\sqrt{3}}$ in order that potential to earth should not be excessive. It varied, however, somewhat, during the tests according to the load. The distance between the generators and switchboard did not exceed 60 yd. so that any effects due to capacity would probably be negligible.

Since there was no return conductor to the neutral point, it follows that the return path for the current was through the remaining two conductors of the three-phase system. The switch in circuit on the high tension tests was of the electrical solenoid operated type, having cone contacts with a break of 10 in. per pole per phase. The whole of the contact mechanism moving in a vertical plane.

The power factor is stated on the diagram, this being the reading taken from a power factor indicator connected up on the circuit. The fact that the diagrams refer to the conditions of one phase of a three phase supply, and also that the voltage is measured between phases and not between one phase and neutral makes it a somewhat difficult matter to draw definite conclusions in respect to the induced pressures due to changes of current, from the records taken.

In all the diagrams relating to the tests on alternating currents, a photographic film must be considered as moving from right to left; that is to say, the current curve which is indicated by the heavy line, appears first, while the voltage shown by the thin line will make its appearance at the moment the current is interrupted.

Results of the Tests

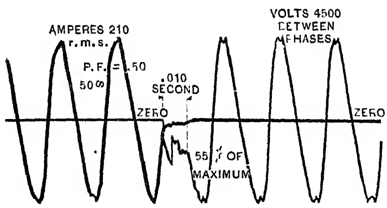
See oscillograms Nos. 33, 34, 35 and 36.

Remarks. Oscillogram No. 33 (210 amperes r.m.s.) shows that the current wave was interrupted as it was approaching zero value. There was an immediate inductive pressure rise, which appears to have been checked very suddenly probably on account of the fact that the impressed voltage wave is endeavoring to establish itself in an exactly opposite direction to the direction of the induced volts. On the other hand, it would appear that it

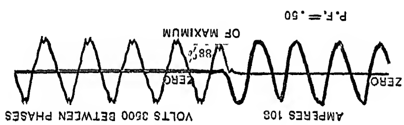
only required a period of time represented by one half of the complete period 0.010 sec. for the voltage wave to establish itself in a normal manner, and it will be noted that the first complete half-wave of the voltage curve reached its normal maximum value.

Oscillogram No. 34 (108 amperes r.m.s.)

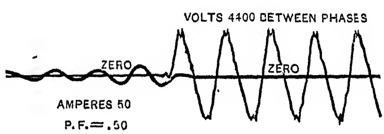
Remarks. In this record the current is interrupted at a point about half-way on the downward curve. It is interesting to



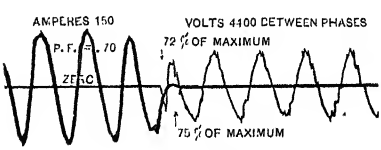
Oscillogram No. 33



Oscillogram No. 34



Oscillogram No. 35



Oscillogram No. 36

note the very sudden reversal of the e.m.f. curve, which again appears to be due to the impressed voltage establishing itself in the direction opposite to the induced volts. In this diagram it will be noted that the half-wave immediately following the rupture of the circuit does not reach the maximum value of the normal voltage wave.

Oscillogram No. 35 (50 amperes r.m.s.)

Remarks. It will be noted that the circuit is opened very soon after the maximum value of the current wave has been reached. In this case the first half-wave of the e.m.f. following the rupture reaches the maximum value under normal conditions, probably owing to the fact that the current broken in this case was comparatively small. The increase of amplitude of the current wave just before the circuit is opened is curious. It is the only record in which this phenomenon occurred. The only explanation the writer is able to offer is, that a growth of the current was commencing at this moment. On the original oscillogram the preceding wave appears to be slightly greater in amplitude, and that wave slightly greater than the one preceding it.

Oscillogram No. 36 (150 amperes r.m.s.)

Remarks. The circuit is opened at a point about half-way on the downward current wave, and here again there is a very sudden reversal of the e.m.f. while the first half-wave does not reach the maximum value of the normal wave.

Conclusions (High-Tension Tests)

In all cases the records show that the circuit may open at any point on the current curve, but after the current has died down to zero value, it never again rises on the other side of the zero line. It would appear, in fact, that in all cases, the oil rushes in between the contacts and prevents an arc being drawn out which otherwise might permit the current to rise again after it has passed through zero value. In one or two diagrams, notably No. 34 there appears to be a slight indication of a current wave having passed through the zero point at break, and risen to a very small value in the opposite direction before the current was finally interrupted but the evidence of the current having actually reached any appreciable value after passing through the zero point is not very definite, as in some cases the photographic records are not very clear, and although every possible precaution was taken to ensure that the diagrams should be reproduced as accurately as possible, the author does not wish to lay great stress on this particular point.

It would appear that the final break invariably occurs at or near to the point where the current curve would, in the ordinary course have reached the zero line. When making these tests, voltmeter and ammeter readings were taken, and where figures relating to current and voltage are reproduced on the diagram, these must be considered as the root of the mean square values of the alternating current of e.m.f. The exact maximum instantaneous values reached by the various curves have not been worked out, but in some cases it will be noted that where the normal maximum value is not reached by the voltage wave immediately following disruption of the current, the height of this wave is expressed as a percentage of the height of the wave under normal conditions. In no case do the tests show any abnormal pressure rises. In fact, the inductive rise on opening

the circuit in no case reached the normal maximum value of the impressed voltage, but it must not be forgotten that these tests were made with comparatively small currents, the greater current broken being 210 amperes, as indicated on diagram No. 33.

E. Zachrisson (by letter): Regarding the influence of power-factor and of different kinds of loads upon the rupturing capacity of an oil circuit breaker, I wish to make a few statements that may be considered as a modest attempt to attack the subject from a theoretical point of view.

The rupturing capacity of a given oil switch is determined by the size and the duration of the arc formed between the opening contacts. If in the circuits to be opened, there is the same current, but different amounts of other electrical quantities, *i.e.*, of voltage between contacts of resistance, of inductance and of capacity, these factors will be the same until the point when the arc will break for the first time, *i.e.*, where the current passes its zero value for the first time after the opening of the contacts. Beyond this point, the conditions will differ materially for the reason that in different cases the arc has more or less liability to be reformed and that the current, if re-established, will reach different quantities. In the following, only the liability of the arc to be reformed will be investigated to some degree, this quantity being dependent on the voltage between the contacts in opening the circuit, and on the point where the highest voltage appears between the contacts, on the moment of opening the circuit or if later; and whether the oil is much carbonized in the path between the contacts at an instant when there is a high potential stress in the oil.

The investigation may be carried out in following cases:

1. The opened circuit contains merely resistance.

The voltage being in phase with the current, it will at extinguishing of the arc, when the current equals zero, also be zero, and will after $\frac{1}{4}$ cycle equal the maximum value. (See Fig. 1.)

2. The circuit opened contains merely inductance (for instance induction coils or an induction motor with open circuited secondary).

When the current is discontinued when zero, the counter e.m.f. of the circuit will suddenly drop to zero according to the equation

$$E = -L \frac{d\,I}{d\,t}$$

and the voltage across the opening contacts will equal the potential of the supply, which is at its maximum value at discontinuing the arc and will thereafter decrease (see Fig. 1). This behavior is very unfavorable on account of the fact that at maximum voltage the oil is about the same as that through which the current has just passed, and which is therefore carbonized and is not as good an insulator as before.

3. The opened circuit contains inductance and resistance in series.

In this case the theory is about the same as in No. 2. The main difference being that the voltage appearing across the opening contacts will amount to only $E_{max} \sin \varphi$, when φ = phase angle of the circuit. See Fig. 1.

4. The opened circuit contains merely static capacity (not to be confused with "rotary condensers").

There the equations apply

$$I = C \frac{d E_c}{d t}$$

$$E_c = \frac{1}{C} \int I \, d t$$

where E_c = condenser voltage.

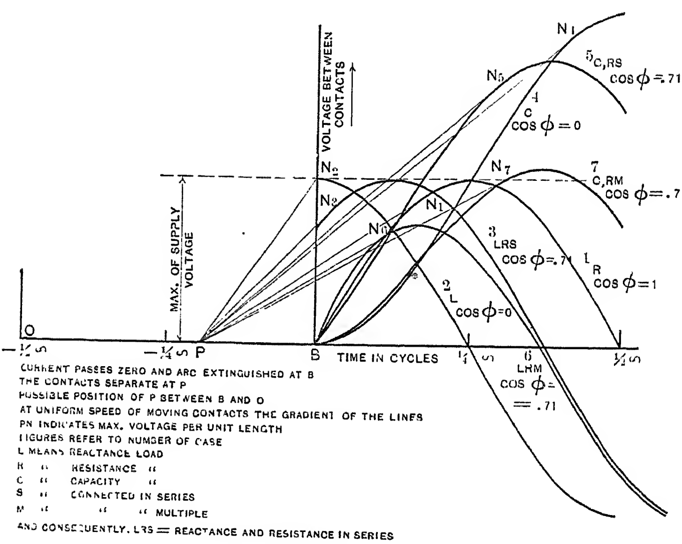


FIG. 1

Accordingly, this voltage E_c is not dependent on the current at the instant when the circuit is opened, and because E_c equals the supply voltage in the same moment, no voltage then will exist between the opening contacts. But this electrostatic voltage found favorable in opening the circuit, will after one-half cycle increase the voltage between the contacts to the double maximum value of the supply voltage. This is rather unfavorable because if there is a reforming of the arc at the highest voltage, a heavy rush of current will cross a large space, burning the oil considerably. Fig. 1.

5. The opened circuit contains static capacity and resistance in series.

With the same arguments as for No. 4, it is readily found that the voltage across the contacts also starts from zero and that its maximum value will be E_{max} $(1+\sin\varphi)$. See Fig. 1.

6. The opened circuit contains inductance and resistance in multiple.

In this case (see Fig. 1 and 2) when the current passes zero and the arc is ruptured, there will still circulate a current I_{max}. $\sin\varphi.\cos\varphi$ through the resistance and the reactance, causing

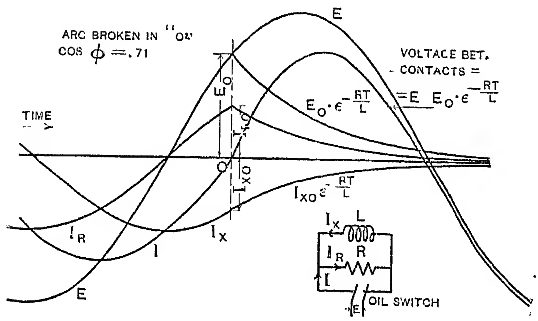


FIG. 2—CASE 6

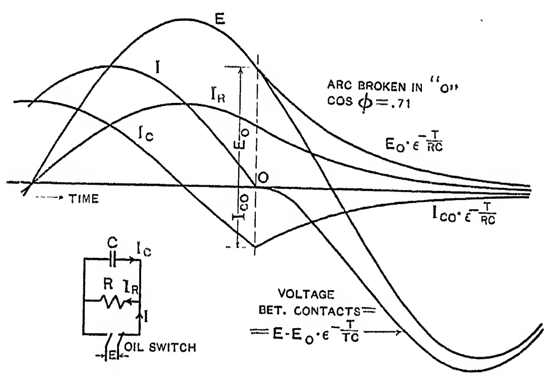


FIG. 3—CASE 7

a voltage E_{max} $\sin\varphi$. This current is decreasing, after the circuit being opened, according to the law

$$I_x = I_{max} \sin\varphi \cos\varphi \, \epsilon^{-\frac{rt}{L}}$$

and causes the voltage

$$E_x = E_{max} \sin\varphi \, \epsilon^{-\frac{rt}{L}}$$

The voltage across the contacts equals the difference between the supply voltage and this voltage E_x.

7. The opened circuit contains static capacity and resistance in multiple.

When the current through the switch (see Figs. 1 and 3) is zero, the condenser is still furnishing the current $I_{max} \cos \varphi \sin \varphi$ to the resistance. This current decreases, after opening the switch, according to the equation

$$I_c = I_{max}\, \varphi \cos \varphi\, \epsilon^{-\frac{t}{RC}}$$

and causes the voltage

$$Ec = E_{max} \sin \varphi \,.\, \epsilon^{-\frac{t}{RC}}\,.$$

The difference between the supply voltage and E_c is the potential across the contacts.

8. The opened circuit consists of two synchronous machines in multiple.

The machines containing reactance and resistance in series, this case is identical with No. 3 except the great difference of the voltage appearing across the contacts of the switch just in opening is not the voltage of the machines, but the voltage drop in the machines, *i.e.*, the geometrical difference between the e.m.fs. of the machines. Here it is to be remembered that these e.m.fs. are created by a flux, formed by the difference between the ampere-turns of the field winding and of the armature reaction. For the magnetic flux is kept practically constant for some time after the disappearing of the armature current because of the effect of the currents, induced in the field winding.

Whether the current of the machines is leading or lagging, the only difference is that the current is discontinued at different points of the e.m.f. wave, so that the voltage across the contacts will show a little difference in wave shape.

9. The opened circuit consists of an induction motor.

If the rotor is open circuited, the case is identical with No. 2.

If the motor is running and the rotor circuit closed the conditions will be rather similar to those of case No. 8. For in breaking the current at the stator, the rotating flux is kept from disappearing at the same time as the current and is kept practically constant for some time by the currents induced in the rotor circuit. Therefore an e.m.f. is induced, that opposes the supply voltage and thus highly diminishes the voltage across the contacts.

Conclusions

1. The difference in the behavior of an oil switch at disconnecting different circuits of the same current is not so much due to just the power-factor of the circuit, as to other conditions, such as how much the impedance of the circuit consists of resistance, inductive and capacity reactance and how these are connected, and if the circuit to be disconnected contains rotating machinery or not.

2. A circuit containing only inductance or capacity gives the most difficult conditions for breaking the current, but the reasons why these two kinds of loads are both so very unfavorable are not the same.

3. At a given power factor of a circuit containing resistance and inductance or resistance and capacity, there are very different conditions if there is a series or a multiple connection.

4. The best conditions for a circuit, that contains no rotating machinery, are when there is only resistance, and if capacity or inductance are in multiple, with a resistance of suitable size.

5. The least difficult work is done by the switch in the case that rotating machines are disconnected. The conditions for this work seem to be many times more favorable than when the circuit contained only impedance.

6. It seems possible that connecting a resistance of suitable size across the load terminals of a switch controlling a circuit containing chiefly inductance or capacity, will facilitate the opening of the circuit in spite of the fact that the total amount of current is increased.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

PROPOSED APPLICATIONS OF ELECTRIC SHIP PROPULSION

BY W. L. R. EMMET

The writer has published a previous paper on the subject of electric ship propulsion and has, in that and elsewhere, given out a good deal of information concerning designs which have been prepared. The purpose of this paper is to describe some of the newest designs of this kind which have been made and to explain some of their features more fully so that their merits may be intelligently considered by engineers who may be interested.

The use of electric motors to propel ships may at first seem inappropriate since with such a method the power of steam must first be converted into mechanical work, then into electricity, and then again back into mechanical work. All of these processes involve appreciable precentages of loss which seem to discourage the undertaking and it is only by the most careful scrutiny of all features that the relative desirability of such an undertaking can be ascertained. Some of the important reasons for the adoption of electricity may however be suggested by the following comparative figures:

	Rev. per min.	Weight lb. per h.p.	Rankine efficiency
12,000 kw. high speed turbine without generator..	1200	8.5	71%
Group of Parsons marine turbines designed to give 28,000 h.p. to four propeller shafts..........	325	42.0	——
North Dakota turbines, two, each 13,000 h.p....	260	——	56%

The large differences shown by these figures are incident to speed, the ship turbine being very large, complicated and ex-

pensive, and relatively inefficient, while the high speed machine is very simple in construction, small, and highly efficient. It is therefore primarily for the sake of speed reduction that we turn to electricity as a propelling force.

It has also been proposed to use mechanical gearing for the same purpose and something has already been accomplished in that direction. The use of gearing for such a purpose is however still practically undeveloped and the requirements are such that the extent of its application is still entirely problematical. In the case of electric propulsion no such uncertainty exists. We have proved by application to other arts that certain results can be accomplished in a thoroughly reliable manner and the designs here discussed simply deal with cases comparable with the simplest and most direct uses of electric power on shore.

The comparison of weights and efficiencies of turbines shown by the figures given above apply only to certain conditions and in other cases the comparison might be very different, so that in such a problem every case must be considered on its merits and its merits cannot be judged until all features of design and operation are worked out in detail. An idea of the requirements of ship propulsion may be given by the following rough statement of conditions:

The power required varies approximately in proportion to the cube of the ship's speed. The speed of revolution of shafts must be suited to the power delivered and the speed of the vessel if good efficiency is to be obtained. There is much difference of opinion concerning the possible relations of propeller speed and efficiency. The following table gives an estimate of propulsive coefficients of a large battleship. These figures are ascertained by comparison of several sources of information and should be considered only as a rough approximation.

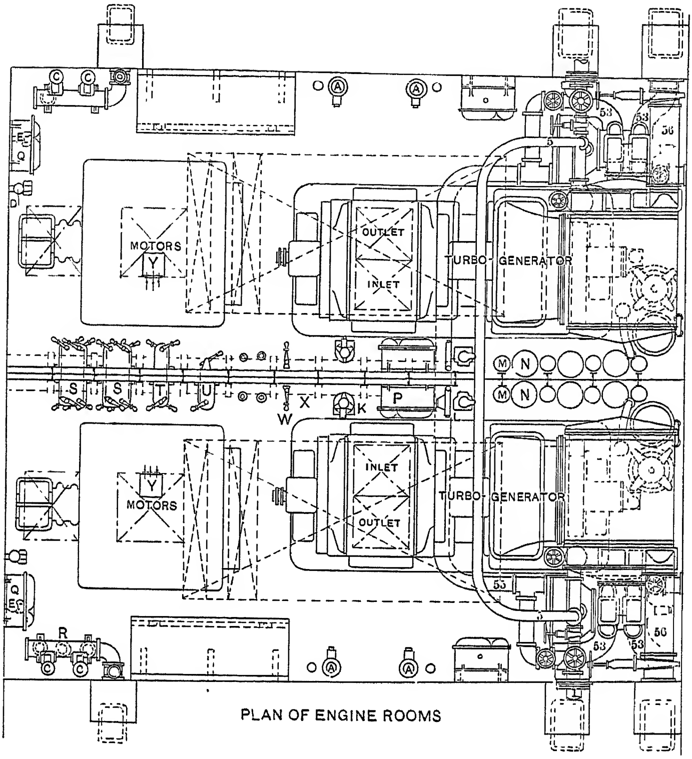
Propulsive coefficients	
Rev. per min.	Two propellers
100	0.56
150	0.532
200	0.507
250	0.485
300	0.470

In all vessels quick stopping and reversal is of great practical value and this quality is particularly valuable in warships. The effectiveness of reversal is dependent both upon the area of propeller blades and upon the torque available for reversal of propellers, so that the requirements of reversal afford an additional reason for desiring low propeller speed, the area of low speed propellers being larger, the tendency to slip is diminished. In some turbine ships, a good deal has been sacrificed for the sake of quickness of reversal and the qualities of different ships in this respect are very different. It may be said that with fairly large and low-speed propellers, a reversing torque equal to 60 per cent of full load running torque will bring a ship up to the best standards of quickness in reversing.

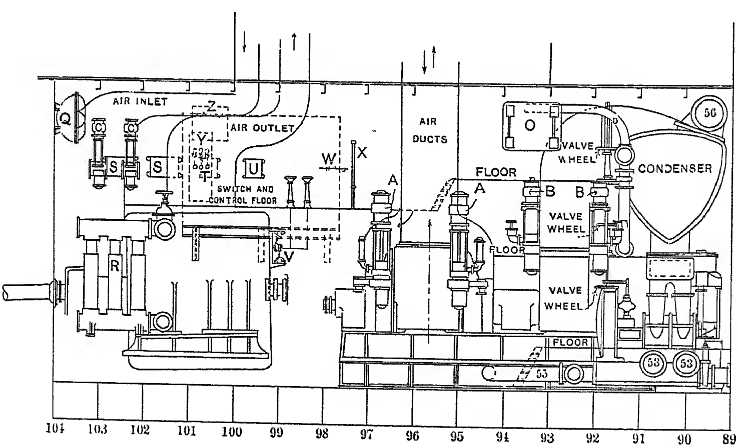
Since practical propeller speeds are always much slower than desirable for turbines, the tendency is to operate marine turbines at speeds below their best point of performance and consequently their efficiency falls off very rapidly with further diminutions of speed. In an electrically propelled ship an excess speed condition can be adopted for the maximum revolutions so that the loss of efficiency with diminishing speeds is relatively less.

One of the important advantages of electric propulsion as compared with other possible methods of speed reduction lies in the fact that arrangements can be made by which the ratio of the reduction is changeable so that the turbine may be run at its most effective speed under more than one condition of the vessel's operation. The possibility of such a change in speed ratio is particularly valuable in connection with warships since such vessels need very high speed for emergency conditions and also need to operate economically at low speed so that their radius of action may be made as wide as possible with a minimum dependence upon coaling stations. It will be seen that these qualities cannot well be combined in a ship whose propellers are driven directly by turbines, even if she is equipped with special turbines for cruising conditions. The importance of high speed being much greater in turbines of small capacity than in large, the cruising turbines which require only a small capacity cannot be made efficient.

In this paper some specific information is given concerning two cases of electric propulsion designs. One of these relates to the apparatus covered by a proposition recently made to the Government for propelling machinery for Battleship No. 35.

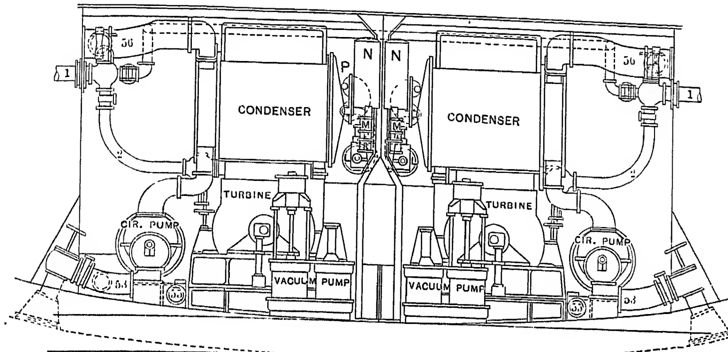


PLAN OF ENGINE ROOMS



ELEVATION OF STARBOARD MACHINERY LOOKING INBOARD

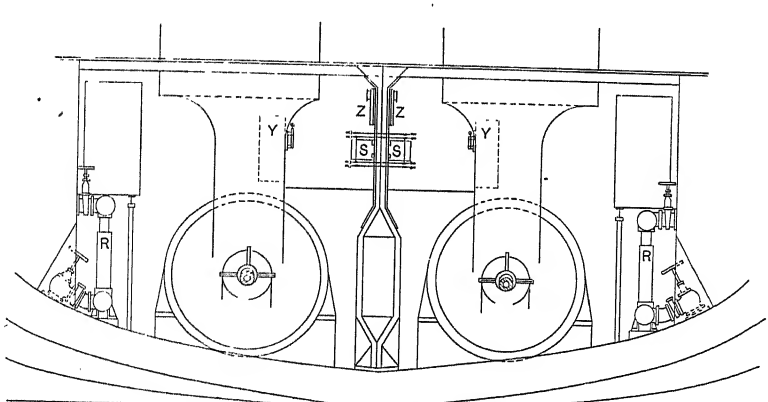
Plan and elevation of propelling apparatus



SECTION AT FRAME 89 LOOKING AFT

AUXILIARIES

A. Main feed pumps.
B. Fire and bilge pumps.
C. Forced lubrication service pumps
D. Fuel oil pumps.
E. Oil cooler circulating pumps.
F. Pipe insulator circulating pumps
K. Auxiliary air pumps.
L. Auxiliary circulating pumps.
M. Air compressors.
N. Compressed air tanks.
O. Feed heaters.
P. Auxiliary condensers.
Q. Oil coolers.
R. Water rheostat.
S. Motor switches.
T. Generator switches.
U. Tie switch.
V. Pole-changing switches.
W. Hydraulic gear operating wheels
X. Liquid tachometer.
Y. Field rheostat.
Z. Switch panel.



SECTION AT FRAME 104 LOOKING FORWARD

Turbine electric propelling apparatus installed in engine-room of battleship with all auxiliaries specified for direct turbine installation.

The other applies to the machinery covered by propositions recently submitted to shipbuilders for propelling machinery to be used in one of the Government colliers recently authorized by Congress. The first of these cases being that of a high speed warship, the arrangement has been made such that two ratios of speed reduction could be used, the change from one to the other being accomplished by changes of connection which accomplish a change in the number of poles of the propelling motor. In the second case no such pole changing is used, the ratio between turbine and propeller being fixed at all speeds.

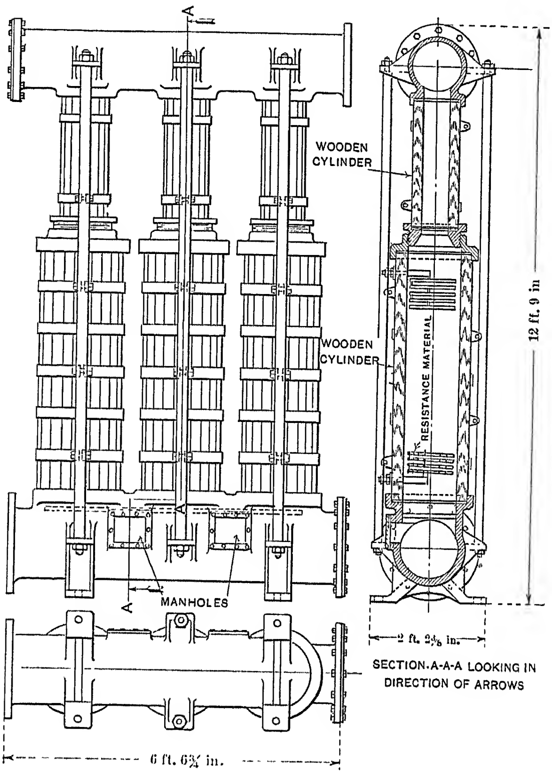
In the battleship, two generating units and four motors are used so that an additional gain in economy can be effected at all speeds by operating with one half of the apparatus in use. In the case of the collier there is only one generating unit and two motors so that all the apparatus is used at all speeds. In the case of the collier however, the speed conditions are very favorable to the turbine and the speed efficiency curve is extremely flat as compared with that of turbines generally used for direct propulsion of ships.

Design Made for U. S. Battleship No. 35

The installation proposed for this ship is shown by the accompanying drawing, which shows not only the electric generating and transmission apparatus but all the auxiliaries which are installed in the engine-room in the Government designs for direct turbine drive. The position of shafts and arrangement of engine-room in this case is identically the same as that proposed by the Government for direct drive by Curtis turbines. The apparatus is installed in two engine-rooms, separated by a water-tight bulkhead. In each engine-room would be installed one 12,000-kw. generating unit and two motors, each having a capacity of about 7,000 h.p. These two motors are coupled together into a single unit and connected to the propeller shaft. One of these motors is of the K type with squirrel-cage armature, the stator windings being so arranged that they can be connected either for 30 or for 50 poles, a suitable group of heavy toggle switches which effects this pole-changing being carried by the frame of the motor itself. The other motor is of the M type with a definitely-wound rotor connected to slip-rings through which an external resistance can be inserted in series. These slip-rings are short-circuited by a very simple and effective sliding spring arrangement. When this short circuit is ac-

complished the external resistance is entirely cut out. This M motor is wound for 30 poles and with its resistance cut out has exactly the same characteristics as the K motor when the latter is worked with its 30-pole connection.

The resistance used with the type M motor is for the purpose of affording the desired torque in reversing, and these resistances constitute a very important feature of the proposed designs

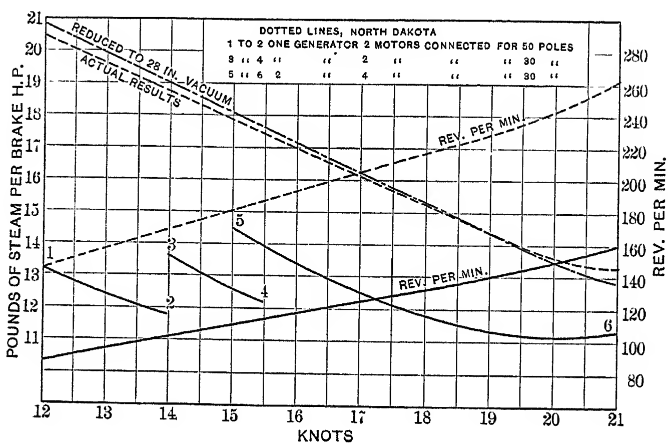


Group of resistances for 7,500-h.p. motor for battleship equipment

since under conditions of reversal they must absorb nearly the total electrical energy of the system. These resistances have been developed by careful experimenting and are capable of accomplishing the desired result in a very compact space and with very large factors of safety. They are made of non-corrosive material and the heat from the electrical energy dissipated is delivered to the sea water which freely circulates

through the resistance compartments by convection. They are easily disconnected and taken apart or, if desirable, renewed and will afford an entirely satisfactory solution of a problem which has sometimes been very embarrassing in large induction motor installations. The accompanying drawing shows the arrangement of these resistances in sufficient detail to be intelligible.

The switching apparatus is so arranged that all switches can be worked from either engine-room, the shafts being carried through bushings in the water-tight bulkhead. When the ship is operated at high speed with both generating units the engine-rooms will be operated separately but when the ship is operated



Performance curve, U. S. Battleship No. 35—pressure 265 lb. gauge, 50 deg. fahr. superheat, 28 in. vacuum

from one generating unit it will be more convenient to control everything from one engine-room and the switches are so arranged that this can be done, the position of every connection being visible and controllable from either side of the bulkhead. The accompanying tabulation and curve sheet shows the propeller speed, horse power, and water rate of turbines for every different speed of the ship and shows the apparatus which would normally be in use under each condition of speed.

The conditions for different speeds are those which will give the best economy and which would ordinarily be used for continuous operation at such speeds but it is possible to vary the speed of the ship up and down with any arrangement of motors

TABLE I

STEAM CONDITIONS—265 LB. GAUGE PRESSURE, VACUUM 28 IN. 50 DEG. FAHR. SUPERHEAT

Knots	12	16	18	19	20	21
Motor speed	87	117	132	140	149	160
Generator speed	1110	895	1010	1072	1140	1220
Shaft brake h.p.	4630	11100	16400	19400	23100	29000
Lb. steam per shaft h.p.	13.2	13.4	11.8	11.3	11.25	11.3

by simply changing the steam admission to the turbines, the only limit being the safe speed and safe carrying capacity of the apparatus. Normally the ship would be operated at higher speeds with two generators and four motors, all of the motors having the 30-pole connection. The turbine speed is then reduced in the ratio of 7.5 to 1, the generators having four poles. When the speed becomes sufficiently reduced improvement of economy can be effected by disconnecting one of the generators and two of the motors as shown by the curve, and when the speed has fallen sufficiently low a still further gain can be accomplished by connecting the remaining motors for 50 poles instead of 30 poles. When this change is made the ratio of reduction is increased from 7.5 to 1 to 12.5 to 1 and a new cycle of favorable speed operation in the turbine is begun. The economy in speeds between 12 and 14 knots is of vital importance in war ships and the very fine economy under these conditions afforded by this design will immensely increase the military value of a vessel so equipped.

Since the power required to propel a ship falls rapidly with diminished speed, and since it is not necessary to maintain any fixed frequency, voltage, or degree of excitation, the magnetic densities of the apparatus can be varied as the speed reduces so as to give the best efficiency consistent with the torque required. With such an equipment the excitation could be derived either from an outside source or partly from an outside source and partly from a direct-coupled exciter. In this case it is proposed to excite from an outside source—the ship's regular circuit —but this excitation can be varied by

a rheostat so that the best possible electric efficiency is maintained.

In the installation here described it is proposed to ventilate the apparatus by air from the upper deck. One duct will convey air to each piece of apparatus and another will discharge it outside the engine-room, the apparatus being so designed as to impel the proper amount of air through these ducts. In this and other cases of electric ship propulsion, it might be desirable to ventilate the apparatus by drawing air through it by blowers and delivering the air so heated to the furnaces. Such a process would effect appreciable economy and would probably be desirable. It has not been considered in this case because there was not time to study the practicability of arrangements.

In this battleship installation it is not proposed to make any changes of connection of circuits, resistances, or poles while the current is flowing. Preliminary to all such operations the field switch will be opened. The switches proposed are of the toggle type, not designed to open under load, and are arranged with electric locks so that they cannot be moved when the system is alive. The turbines are arranged with speed governors of the ordinary type which are capable of closing any valves which may be open if the speed rises. The number of valves which can be opened at any time is, however, governed by hand control and the speed governor is incapable of adding to the number so opened. When the field circuit is interrupted the generating unit rises to its maximum speed and runs idle until the circuit is re-established. In the meantime the desired connections are made and the field re-established, whereupon the generator and motors resume the proper speed relation and proceed to accomplish the desired result.

When these electrical conditions are considered it will be seen that an immense advantage results from the fact that they are not bound to any fixed frequency or voltage. The generator is designed simply to do the work required of it and it is incapable of delivering a current in excess of the safe carrying capacity of any conductor in the system. No kind of wrong connections can result in any burn-out. If a wrong connection should be made it would simply be necessary to open the field circuit and change to the proper connection, and the currents resulting from such wrong connections would not be harmful since the mistake would be apparent and soon corrected. The case is therefore very different from that of an ordinary electric circuit

where all sorts of needs must be provided for from a source of fixed potential and where the generating plant constitutes a battery capable of delivering power in indefinite quantities, either for use or for destruction in the case of short circuits or wrong connections.

The following is a list of the weights of the different parts of the installation proposed. The aggregate weight of these parts is probably not much less than that of the turbines alone which would be used for direct propulsion. The generating units in this case however include heavy cast iron bases and there would be a considerable saving on account of the supporting structures which would be used with turbines for direct propulsion. The absence of any system of forced ventilation also increases the weights. In other cases of battleship propulsion which have been studied, considerable savings of weight have been effected and it is believed that with the best arrangements, similar economies could be accomplished in this case.

Two generating units	674,000 lb.
Accessories	2,600 "
Four motors	408,000 "
Switchboard and switches	5,000 "
Field rheostats	1,600 "
Water-cooled rheostats	6,000 "
Cables	17,800 "
Total weight	1,115,000 "

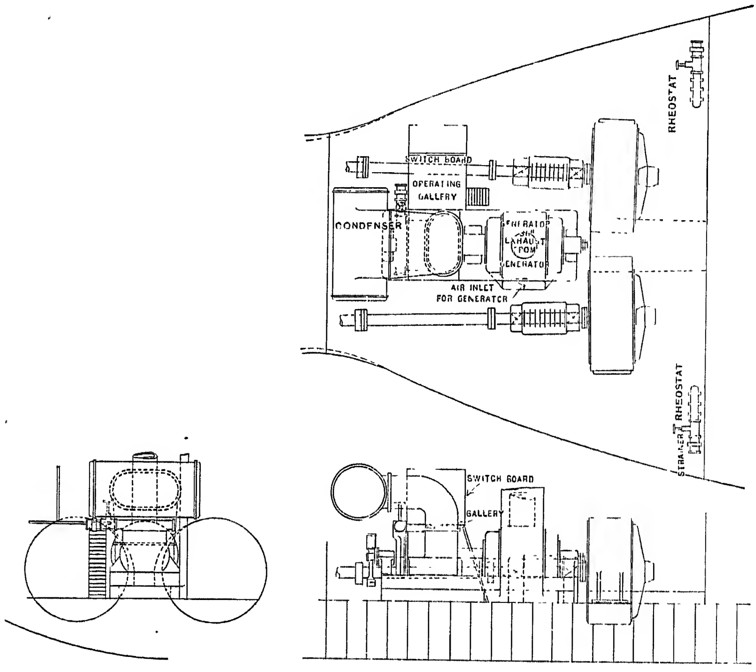
Equipment for Naval Collier

The installation proposed for this collier is similar in general principle but much simpler than that proposed for the battleship. The requirements of this ship being to operate continuously for long periods at a speed near the maximum, there is no particular need for high economy at lower speeds and it therefore becomes desirable to simplify the apparatus as much as possible in the interest of lightness, cheapness, and good economy at the normal operating speed of the vessel which would be about 13 or 14 knots. In this case only one generating unit and two motors are used.

Another difference between this case and that of the battleship is that it is proposed to use oil switches so that changes of connection can be made without the trouble of interrupting the field circuit. When the resistances are in circuit in the motors, either propeller could be reversed independently by simply throwing the lever of an oil switch. This quality of instantane-

ous reversal would be valuable in a ship of this kind since such large freighters steer very badly at low speeds so that it is very desirable to steer by the propellers in anchoring or docking.

For this collier installation the method of ventilation proposed is somewhat different from that in the case of the battleship. The generator would be ventilated in the same way by a duct from the deck above and another duct to take away the heated air. In the case of the motors it is proposed to take the ventilating air from the engine-room and deliver it to the suction

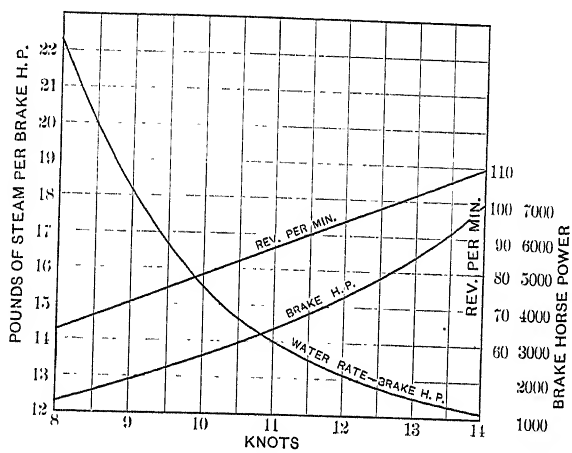


Turbine electric propelling apparatus installed in engine-room of Collier with condenser but no other steam auxiliaries shown

of a blower which puts air into the Howden draft system of the after fire room. This would afford effective ventilation for the motors and about the right amount of ventilation in the engine-room without the use of any other blowing apparatus.

The accompanying curve sheet shows the steam consumption per shaft horse power which would be required with this apparatus at different speeds of the vessel. These results are susceptible of exact calculation since generating units and motors almost exactly similar to those proposed have been repeatedly

tested. It is very difficult to get at any accurate estimate of the steam consumption of such a ship when operated by reciprocating engines but all comparisons which have been made indicate that the turbine electric apparatus would effect some economy in steam consumption, although it is probable that the saving as compared with the best engine equipment would not be very large. The demand for electric propulsion on one of these colliers has come from the Navy Department through a desire to demonstrate the practicability of this method of propulsion. The case is not particularly favorable to electric propulsion and should not be taken as a basis of comparison of the system with other methods. Electric propulsion will make its best showing in vessels requiring a very large amount of power

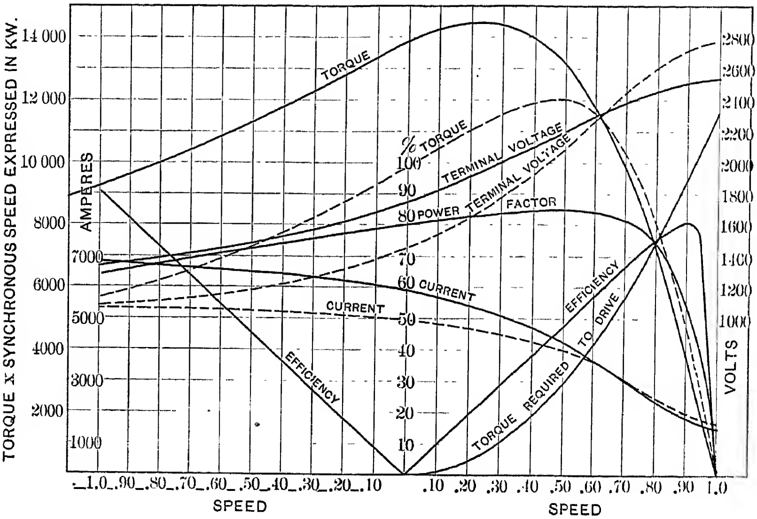


Performance curve, electric drive, U. S. Collier—190 lb. gauge; 0 deg. fahr. superheat; $28\frac{1}{2}$ in. vacuum—displacement about 20,000 tons

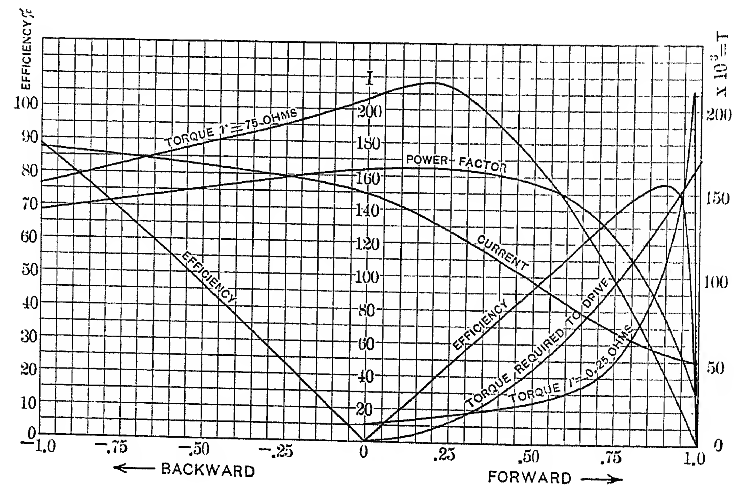
or vessels which require a good economy at low speeds as well as at high. High-speed warships or very large moderate-speed liners afford the best fields for its application.

Electric Characteristics

The accompanying curve sheets show the characteristics of the combined action of motors and generators proposed for these two installations. Two of these sheets show conditions of operation or reversal with resistances in circuit, and the other shows the conditions in the collier installation without resistance in the motor circuits and with the generator operated at various speeds. From these curves the torque available under any condition of operation and also the current, voltage, and

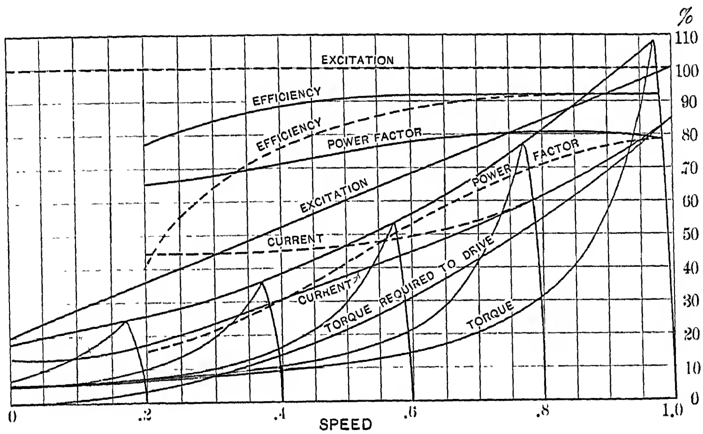


Battleship No. 35.—Conditions of combined operation of motors and generators with reversing resistance in circuit and generators at full speed. Dotted lines show torque, voltage and current when only one generator is used. The power factors and electrical efficiencies are about the same with either one or two generators. External resistance 0.207 ohms per phase, rotor resistance 0.0069 ohms per phase



U. S. Collier.—Showing conditions of combined action of generator and motors with reversing resistances in circuit and with generator at full speed. External resistance 0.75 ohms per phase, rotor resistance 0.025 ohms per phase.

necessary excitation can be seen or readily estimated. No curves are given to show the conditions of operation without resistance in the battleship installation because the characteristics under such conditions are virtually the same as those in the collier and are sufficiently illustrated by the curves given in the case of the collier. These curves show the effect of different degrees of excitation upon power-factor and efficiency. As a vessel so propelled is slowed down, the excitation could be reduced in proportion to the propeller speed and the maximum degree of reduction in excitation will give the best electrical efficiency. From the curves here given, however, the decline of excitation



U. S. Collier.—Showing condition of combined action of generator and motors with varying speed of generating unit and with no external resistance in rotor circuit. Dotted lines refer to constant full load excitation. Full lines refer to variable excitation. Torque curves of motor are given separately for different fixed generator speeds. All other curves apply to normal conditions where speeds of motors and generators vary together.

is less rapid than that of the speed, this degree of diminution being chosen so as to give an ample margin of torque under all possible conditions of operation. In practice, whenever the ship is operated under any fixed condition of speed, the excitation should be reduced to the lowest possible point necessary to maintain the required torque on the propeller. Since the margin of torque assumed in the curves given is very ample, the electric efficiencies would be even better than those indicated by the curves.

In connection with this paper which gives specific information concerning two sets of designs, the author has thought it desirabl

TABLE 2

Case	Dis-place-ment tons	Shaft h.p.	Approx. wt. main eng's or turbines tons	Weight of corresp. electric drive	Speed knots	Rev. per min. elec. drive	Water rate elec. drive without aux. lb. per shaft h.p.	Steam conditions
1	19,360	6850	335	135	14	110	12.0	200 lb. gauge, 28.5 vac. dry.
2	25,000	12500	411	237	16	110	11.5	" " " "
3	20,000	3400 17300	435 "	374 "	12 20	87 148	12.85 11.5	260 " " " 50 deg. superheat " " " 28.0 "
4	10,945	2275	102	55	10.5	85	13.0	175 " " " dry
5	9,900	5500	—	133	14.6	114	12.5	181 " " " "

to give also some figures concerning other cases which have been studied with greater or less degrees of thoroughness in order that an idea may be formed concerning the relative desirability of such methods in connection with ships of different kinds. The accompanying tabulation gives some such figures:

Some of these designs for apparatus to propel ships have been criticized on the ground that the weights of electric apparatus shown were small in comparison with weights of similar kinds of apparatus used on shore. This is to some extent true, first because the structural part of these devices has been designed with a view to economy of weight, although the designers have not gone nearly as far in this direction as it would be possible to do; and secondly because this ship apparatus is rated on a maximum output basis, whereas apparatus for other purposes provides for overload. There have been some further weight economies possible on account of the special conditions relating to the operation of such apparatus. A careful comparison with a number of cases where large apparatus of similar character has been installed on shore shows that on a basis of very reasonable temperature rise, the magnetic weights in all cases agree closely and that these electrical designs are in every respect normal and conservative.

Discussion on "Proposed Application of Electric Ship Propulsion", Schenectady, February 16, 1911.

C. P. Steinmetz: Mr. Emmet's paper on electric ship propulsion describes one of the most important and material advances in modern marine work, and more particularly in that highest product of naval engineering, the modern battleship. In the propelling machinery of the ship, the condition which is foremost, before anything else, is to secure the highest possible weight and space economy, and the power economy to some extent is of importance only in relation as it determines the weight and space economy, especially so in military vessels. Any decrease of the weight and space of the propelling machinery means more space for coal, any increase in the efficiency of the propelling machinery means more distance traveled or higher speed, with the same amount of coal.

The two most important requirements of the military vessel are the highest speed in action and the greatest radius of operation at cruising speed.

Of all the prime movers available in ship propulsion, the most efficient one is the steam turbine. The internal combustion engine may sometime be developed. At present its weight is not such as to make it worth considering where large amounts of power are required. However, the steam turbine has some serious disadvantages in its use for ship propulsion. It is essentially a constant speed motor, analogous to the shunt motor, while the reciprocating steam engine is a varying speed machine similar to the series motor, that is, in the reciprocating engine, the theoretical thermodynamic efficiency is independent of the speed, while in the steam turbine it is maximum at a certain definite speed, decreasing above and below this speed. For many fields of ship propulsion, constant speed is suitable, as in the transatlantic liner, etc. But in the battleship, we must have two economical speeds: one very high speed, the speed of action; there we require the highest possible efficiency to get the maximum speed, since the existence of the ship, its life, may depend on its rapid movement. But this speed is used rarely; many ships may pass through their lives without ever being called upon to develop that higher speed except in trial runs, because it is only used in battles. A much lower economical speed is essential for efficient cruising; the cruising speed, about 60 per cent of the racing speed. The operating radius of the ship, and thereby its usefulness, depends on the efficiency at this speed, and maximum efficiency thus must be reached at this cruising speed as well as at battle speed.

A constant speed machine such as the turbine, is not suited to operating at very different speeds with equal, and highest efficiency, but an electric motor can do that. We can have an electric motor operating with equal efficiency at two or more speeds, and therein lies one of its advantages.

At first sight the method of interposing between the turbine and propeller shaft an intermediate link, the generator and motor, appears indirect, and therefore less desirable than the direct drive of the propeller. However, such objection does not apply where electric power is used, because after all, all applications of the electric motor are indirect, intermediate links between a prime mover and the load. The electric motor does not generate power, but merely delivers the power which is generated somewhere else. It is an indirect method of supplying power where it is being used. That it is used to a rapidly increasing extent, is due to the superiority of the electric drive in its flexibility, convenience, reliability, etc. For instance, in the case of long distance transmission. We cannot bring the water power to the city, but we can take the motor to the end of the transmission line. We cannot put a steam engine at every group of machines, but we can have a highly efficient steam engine or turbine driving the generator and have a motor at every shaft. In ship propulsion, the advantage which we gain by the motor are its flexibility, especially regarding speeds. The economical speed of the steam turbine and the economical speed of the ship's propeller are widely distant, and it is not possible to compromise between the two and get both speeds together without a material sacrifice of efficiency, as the history of all steam turbine ships has shown.

The steam turbine is essentially a high speed machine, since steam is the operating medium in the turbine, and the velocity of rotation must be related to the velocity of the medium. The velocity of steam expanding from boiler pressure to a vacuum is nearly 2000 meters per second, over a mile per second. This velocity is from two to three times as great, the kinetic energy from four to nine times as great as that of the modern high velocity rifle bullet. It is a speed which would carry us across the continent from New York to San Francisco in less than one hour. This speed we have to control in the turbine engine. We break it up into a number of steps. But we have to realize, when we use a number of expansion steps, we subdivide, not the velocity, but the energy which is proportional to the square of the velocity; to get down to low velocities in this manner, means very many expansion steps, and a correspondingly low space and weight economy, and also lower power efficiency. That is, the low speed steam turbine is inefficient.

Some data on efficient propeller speeds are given in Mr. Emmet's paper. This data to my mind does not yet represent the actual conditions because they give the propeller as operating under normal conditions. We know that in any apparatus when you compare the different possibilities, it is not only the normal condition of operation, but the emergency or abnormal conditions, which are the criterion on which we have to rely in judging reliability, etc. The greatest emergency in ship propulsion is the rapidity of reversal, when the propeller is called

upon to give the maximum possible torque to stop the ship as quickly as possible, because the existence of the ship may depend on the rapidity of stopping. This is the condition where the difference between the high-speed small propeller and the slow-speed large propeller is greatest, because the maximum thrust which the propeller can exert, depends on its diameter, and is a function of the square of the diameter of the propeller, that is, the thrust per unit area of the propeller, positive at one side, negative on the other side, is limited. On the negative side, the suction thrust can not exceed the pressure exerted by the atmosphere and the head of water, and is between one and two kilograms per square centimeter. If we try to drive faster, a vacuum is created, and the propeller does not act properly on the water any more, looses its grip, what is called cavitation. The thrust at which cavitation begins, is depending on the square of the propeller diameter, that is, the area of water acted on by the propeller, and here it is where the low speed, large propeller shows its greatest superiority in its effective operation in reversing, accelerating, stopping. Thus, the high-speed propeller is inferior in efficiency, and control. As the result, in its application directly to the ship's propeller, the steam turbine is greatly, and in slow-speed ships, as colliers, almost hopelessly handicapped, and at the best, in high-speed transatlantic liners, gives a performance greatly inferior to that, with which we are familiar in the high-speed turbines of all electric generating stations.

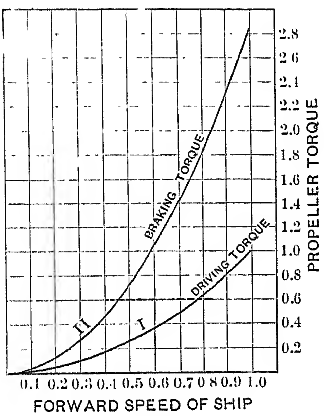


Fig. 1

One of the most important advantages, which the use of the electric drive holds out, is the possibility of a much more rapid stopping and reversing of the ship, more rapid than the steam turbine or even the reciprocating engine can give. The curves given in Mr. Emmet's paper show a full speed reversing torque of the motors as 133 per cent of the torque required to drive the ship forwards at full speed. It is obvious that in a flexible apparatus, such as in the induction motor-generator, we could, by changing the rotor resistance, increasing the generator excitation, and draining the boilers of steam by feeding momentarily an excess of steam into the turbines, still greatly increase the reversing torque, to practically any reasonable value, if it were needed. But the paper states that it is not needed, since experience has shown that the condition of reversal is satisfied by a reversing torque equal to 60 per cent of full load torque. This appeared somewhat startling, and it took me some time to grasp its significance.

The paper shows the torque required for the propulsion of the ship, as function of its speed. This is reproduced as *I* in Fig. 1, in fractions of full speed torque.

The torque required to drive the propeller backwards for different forward speeds of the ship, is shown, approximately, as taken from tests of propeller models, by curve II. It is given in fractions of the torque required for full speed forward drive.

As seen, at full forwards speed of the ship, it would take nearly three times full load torque, to start the propeller backwards. The torque of 60 per cent of full load torque, which is claimed to be sufficient for reversal, is reached at a ship's speed of 46 per cent of full speed. That is, with a reversing torque equal only to 60 per cent of full load torque, the propeller could be started backwards only after the ship has spontaneously decreased in speed by the water friction, to less than half speed.

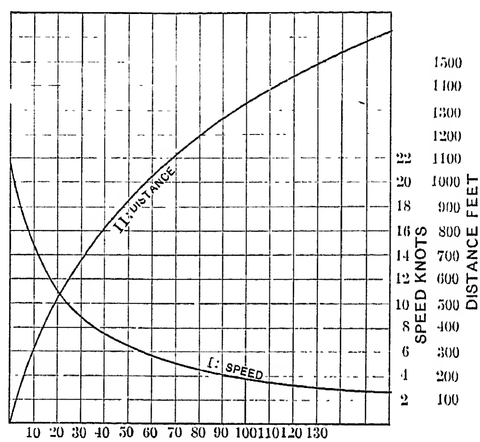


Fig. 2

If then 60 per cent of full-load torque is sufficient for reversal, it seems, that the time required in stopping and reversing the reciprocating engines or turbines is so long, that in this time the speed of the ship has decreased greatly, and the ship traveled forwards a considerable distance.

In curve I of Fig. 2 is given the calculated deceleration curve of a typical battleship of 20,000 tons. As seen from curve I of Fig. 2, the initial deceleration is very rapid, and 46 per cent of full speed is reached after 24 seconds. During this time, the ship has traveled 580 ft., as seen from the time distance curve II of Fig. 2.

With a reversing torque equal to 60 per cent of full torque, the ship would thus have traveled 580 ft. before the propeller begins to retard. With the electric drive, it should be possible to reverse the motor in emergencies in five seconds or less, that is,

after the ship has drifted only **150** ft. or less. Then a reversing torque of 1.87 times full load torque would be required, and the drift of the ship would be reduced by over 400 feet.

It thus seems, that the introduction of the electric drive would not only give an increase of space, weight and power efficiency, and thereby an increase of the maximum speed and an increase of the cruising radius of the ship, but also a material increase in the promptness of control, especially under emergency conditions, as exemplified by a great increase of the rapidity of stopping the ship from full speed.

Gano Dunn: The subject of the moment is another demonstration of the old adage that the longest way around is often the shortest way home. We saw this first demonstrated when it was proposed to introduce electric drive into factories.

There was no dispute that a revolving shaft would more efficiently transmit a given power to a given place, yet as a system of distribution the electrical method was far ahead in efficiency and had many other advantages besides.

The Heilmann locomotive was a second demonstration. This locomotive might be described as one of Mr. Emmet's ships on a railroad track. It was an attempt to dissolve the affectionate connection that for so long had existed between cylinders and wheels and the reason it has not been heard from, as I believe Mr. Emmet's ship will be heard from, is it did not have the advantage of turbine efficiency and cost in its prime mover.

In the ship of the paper there are no cylinders to be divorced, the turbine and propeller each chooses its own condition of maximum commercial efficiency, high speed for the one and low speed for the other. Independence of direction of rotation, advantages of remote control, and remarkable facility of adjustment are linked together by an electromagnetic connection that renders these advantages possible.

It is advantages like these that stand out so strikingly in Mr. Emmet's paper and not solely the advantages of efficiency that are behind the enormous and rapid growth of electrical applications. This growth is because we can do things by electrical methods that we cannot otherwise do.

It might be said that until the present generation our only means of transmitting power was matter. We had mechanical systems and the distances over which they could operate and the things they could do, were limited, but now we substitute ether and receive such lavish endowment in increased flexibility, adaptability and efficiency that we are affecting the character of civilization.

It is unfortunate that turbines and propellers are most comfortable at the opposite ends of a wide range of speed.

An enormous amount of attention has been given to the development of a mechanical gear for connecting them, and efforts have been turned in the direction of making this gear more or less flexible.

The electromagnetic connection which Mr. Emmet's paper describes is flexibility in perfection. It gives that soft and fluffy contact between the power and its work that the flexible gear men are trying so hard to get in their mechanical devices.

It is no small pleasure as electrical engineers that we see a third important mechanical problem solved by electrical means, and as usual, the solution solves more than the problem. We are presented with advantages of control and adjustability that we were not looking for.

Maxwell W. Day: It is characteristic of Mr. Emmet to take large steps in advance, rather than small ones, and this case is not an exception as the following facts show.

There are three small vessels in Europe of 1150 tons and less, using internal combustion engines with generators and electric motors, two of these vessels being arranged with magnetic clutches so that reversing and manouvering can be done by the electrical equipment, but at full speed the magnetic clutch is thrown in and the propellers are operated directly from the engines.

The German Navy has a salvage ship for submarine torpedo boats operated by steam turbo generating sets and electric motors. This vessel is used for charging, docking, and raising submarine torpedo boats.

In our own country the two principal cases are those of the Chicago fire boats, equipped with turbine driven generators and electric motors, also operating on the Leonard system. These boats can be perfectly manouvered by the pilot without the use of any signals to the engineer. With the electric arrangements proposed by Mr. Emmet for handling the largest vessels, the time for stopping and reversing the propellers will be very much reduced from the time required in the present steam practice. I noticed particularly the long time required for this on the Steamer Harvard, as the signal from the pilot must be answered by the engineer, one throttle closed and another opened in order to reverse the propellers.

W. B. Potter: It has been suggested that it would be of interest in connection with Mr. Emmet's paper on electric drive as applied to marine service, to mention something concerning electric drive as applied to self-propelled motor cars using a gas engine for prime mover.

The gas engine and the steam turbine have a similar characteristic in that both are materially affected by a decrease in the number of revolutions. For reasons of economy with respect to weight and fuel consumption, it is desirable that the gas engine should be no larger than necessary to deliver the power required to drive the car at full speed. The electric drive provides a means of delivering the full power of the engine from the moment of starting up to full speed with a tractive power inversely proportional to the speed and limited only by the slipping of the driving wheels.

It might reasonably be asked why a mechanical drive would not be as suitable for these large cars as for automobiles, especially since the cars run on a smooth track with much less friction per ton than rubber tired vehicles on an ordinary roadway. The value of the electric drive lies principally in its ability to provide the high tractive force required to accelerate the greater mass of the motor cars, which weigh from 35 to 50 tons. To do this with mechanical drive and utilize the power of the engine as advantageously as with electric drive, would require a prohibitive number of gear changes.

The maintenance of the schedule is an important factor in the operation of a motor car and to accomplish this, it is very desirable that the power of the engine be used to the best advantage during acceleration. The generator, which is directly connected to the engine, is provided with a field control regulated by a switch operated by the engineer. This switch is located within the controller which also has contacts for connecting the motors in series or parallel and for reversing the direction of movement in the manner usual on a trolley car.

Reliability of operation with respect to the transmission of power from the engine to driving wheels, is well insured as the apparatus and devices used are similar to those on electric cars.

The cars are usually from 56 ft. to 70 ft. long and are divided into compartments to provide so far as the service is concerned, a complete train within a single car. The supply of fuel carried is sufficient for a run of approximately 200 miles.

Electricity has been generally considered in connection with transmitting power to a distance but its advantages as a flexible connection between the prime mover and utilization of the power, do not seem to have been fully appreciated. In both marine and railway service I believe the electric drive has an important field of development.

H. A. Mavor (by letter): The propositions made by Mr. Emmet and the calculations there anent are of the greatest interest and it is reasonably certain that the claims which Mr. Emmet makes for economy can be fully realized, but the machinery arrangements shown in the paper are liable to hostile criticism from marine engineers. They would doubtless be justified in saying that while the arrangements shown would be perfectly feasible and probably quite satisfactory on a land installation, at sea the use of such appliances in the manner described and on the scale proposed would be a somewhat bold experiment. The writer of the paper would doubtless be the first to admit that confidence in such arrangements must grow with experience.

Apart from any objections which may be made by marine engineers it is evident that in laying down a scheme for marine propulsion the simplest possible expedients should be adopted and for this reason it appears to the present writer that all arrangements requiring the use of delicate instruments of pre-

cision, or of resistances to absorb large powers, or of subdivisions of the plant and arrangements thereof which involve running generating units in parallel, are to be scrupulously avoided. The general objects to be attained may be stated as follows:

1. To provide a simple, trustworthy, and economical means of adapting the power generator to the propeller so as to permit of differences in speed essentially associated with the different characteristics of the power generator and the propeller.

2. To provide means for changing the speed ratio between the generator and propeller so as to permit of the power of the generator being developed under the most favorable conditions at all speeds of the ship. This change of speed ratio should be accomplished without interfering with the efficiency of the apparatus under full speed conditions or with the satisfactory design of the equipment.

3. To provide a ready means of reversing the direction of rotation of the propeller without changing the direction of rotation of the power generator.

4. To provide means for applying the power of one or more engines to one or more propellers so that the power generating units may be so disposed as to give the highest efficiency and when they are not required they may be stopped.

This object should be attained without the necessity for paralleling the electric generators.

Mr. Emmet's proposals appear quite satisfactory in respect to object No. 1.

In respect to object No. 2 it does not appear that the pole-changing devices can be reduced to the simplicity necessary for satisfactory operation instantaneously at the word of command or signal from the bridge.

The third object Mr. Emmet appears to have satisfactorily attained.

The fourth object is more difficult of attainment by ordinary methods. The writer believes he has solved the problem by two methods which have been described by him in a paper read before the Institution of Civil Engineers in London, December 1909. For most purposes where there is more than one generating unit, in the present writer's opinion, the motor described in that paper, meets the conditions in an extremely simple and effective manner. Each motor has as many windings as there are power generators on the ship. These windings are absolutely normal in character and the pole numbers are so designed that they all suit the same slot number. At full power each generator feeds into its own winding and if the windings are so arranged in respect of pole numbers that they are mutually non-inductive the generators do not require to be synchronized or run in parallel and may be switched in anywhere near the proper speed. The pole numbers of the several windings need not be very far apart but of course they must all result in association with generator periodicity in the same shaft speed.

The writer has built and equipped a small vessel to illustrate the principles on which a plant of this type can be worked and he has been astonished to find how difficult it is, even with so simple an equipment, to keep down the number of parts and to preserve the straightforward character of the work. It must not be forgotten that while in many respects the marine engineering problem is much simpler than ordinary transmission of power on land and that many of the difficulties with which the land engineer is faced are entirely eliminated at sea, there is one prime requirement which must be kept in hand and every necessary artifice adopted to preserve it, *viz.*: That the engineer shall be able instantaneously to produce the result called for by the working of the ship. He must not have to stand and wait till his plant is run up to synchronism before he can close his switches. The few seconds required to do this may give time for a collision to occur or for the ship to go ashore.

Experience in the use of the "multiple motor" equipment has already shown that the alternating current applied in this way is beautifully adapted to the purpose and is infinitely superior to any conceivable continuous current arrangement. To bring out this point would require a full description of the machinery and trials, and as the experimental vessel has only done preliminary trials the time has not yet come for describing them, but the results so far are very encouraging. There does not appear to be any need for resistances in the secondary circuit.

C. H. Peabody and H. G. Knox (by letter): This paper by Mr. Emmet, on account of his previous experience in the Navy and his present position in a great electric company, challenges both our attention and our appreciation of his attempt to solve one of the most difficult engineering problems of the day.

The limited application of steam turbines to the direct propulsion of ships is well understood—by none better than by turbine builders. To extend their range, a number of devices, mechanical and electrical, have been proposed; though none has yet won its way to general acceptance, it appears likely that some or all may succeed when applied to merchant ships.

The most difficult problem of all is that to which Mr. Emmet has turned attention, namely obtaining a good steam efficiency for battleships, both at full speed and at cruising speeds. A mechanical reduction gear, if applicable to the enormous power developed on battleships, might give some amelioration of conditions for both services, but would be subject to the mechanical compromise now accepted both for reciprocating engines and turbines. None of the several electric devices preceding that offered by Mr. Emmet, such as the use of induction generators, frequency changers, and induction motors in concatination, appear to be adapted to warships, for though they offer several speeds, there is no provision for that nice adjustment of speed required for station keeping. The combination of pole changing coupled with rotor resistance, and direct control

of the speed of the turbines proposed by Mr. Emmet, appears to meet this feature completely. This and his estimated steam economy at all speeds makes his proposition exceedingly attractive, especially as he claims for it simplicity, strength, and light weight.

Naval architects generally have comparatively limited acquaintance with large electrical undertakings involving the use of alternating currents, and may not appreciate the precisions that can be assured to computations of electrical efficiencies and steam economies of turbo-generators; they can, however, understand the weight that must be given to the results offered in this paper. They entirely appreciate the advantages of choosing favorable conditions for the propellers.

Sea-going men may look askance at a voltage of 2700 proposed by Mr. Emmet as a maximum in his device; but this is only a little in excess of standard voltages in common use for all sorts of purposes in all sorts of places. In reality the conditions on shipboard are comparatively favorable especially in the engine room. The leads carrying the great currents at high voltage are short and can be completely protected so as not to call for apprehension; certainly not so much as steam pipes with 260 lb. pressure.

The resistance units may need to be demonstrated under actual conditions, especially to show that convection currents in the cooling water are sufficient to take care of the heat generated at an enormous rate, even though it be admitted that the action is momentary; attention should be called to the fact that the resistance grids displace a considerable volume in the cylinders containing them, and also impede the circulation. Perhaps a circulating pump may be desirable until experience has been had.

Mr. Emmet emphasizes the advantages of a large propeller and a good torque for stopping and reversing, and estimates that 60 per cent of the full load torque would be sufficient. He doubtless has in mind that the torque should be applied gradually or there may be danger of excessive stresses in the propeller blades.

After what has been said concerning precision of computation of electric efficiency and steam economy, we must not carp at his estimated steam consumption per shaft horse power; they are certainly very favorable when from them allowance must be made for frictional and electrical losses. In this connection it may not be out of place to call attention to the reported water rate of the *Harvard** which used 14.7 lb. of steam per shaft horse power in the turbines. This may be allowed to emphasize the objection to the trial of Mr. Emmet's schemes on a collier, when, truly, it may demonstrate its practicability, but not its efficiency; especially as tested against a turbine with mechanical reduction gear.

* Trans. Society N. A. & M. E., 1908.

A paper presented at the Pittsfield-Schenectady mid-year Convention of the American Institute of Electrical Engineers, February 16, 1911.

VOLTAGE REGULATION OF GENERATORS

BY H. A. LAYCOCK

The voltage regulation of generators was recognized to be an important factor in central station operation as early as the first installation of the Edison bi-polar generator. At the time these generators were first installed it was found that owing to the poor regulation of the prime movers, which were very poor regulating engines, that with fluctuating loads lighting was not very satisfactory when connected to the same dynamo which operated power loads, and in order to produce constant voltage a regulator, which was practically an automatic rheostat having the rheostat switch controlled by a solenoid, was designed.

Since the days of the Edison bi-polar machine, with the advancement in electric generators, voltage regulation has become more and more an important factor, and in order to obtain this regulation some of the first alternators were designed with compounding fields. This was the old type of revolving-armature machine in which the compounding was affected with a series field or current transformer action—the additional turns on the auxiliary field increasing the voltage as the load came on. While this alternator was fairly close in regulation if the load was not too severe the speed regulation was still a factor over which this type of machine had no control.

Various devices have been exploited with a view to obtaining voltage regulation, but most of them have been based on the principle of the automatic rheostat, which has been unsuccessful due to hunting and also to the fact that in order for a rheostat to come into operation the voltage must first vary, and of course the moving element being slow the voltage would vary consid-

erably before the regulating rheostat would operate. This was little better than hand control.

In order to obtain good regulation on the standard alternators of to-day it is necessary to take into consideration the following conditions:

First, the inherent regulation of the alternator. If the alternator is a good inherent regulating machine and is one which is designed at fairly high saturation with a given excitation it is supposed to regulate within 8 per cent with a constant speed; but again, the speed changes are not taken into consideration. In order to obtain the best voltage regulation from an alternator without an automatic regulator the exciter is also run at a high density and is usually compound-wound so that it will either give the same excitation from no-load to full load or will be slightly over-compounded to take care of the increased load, and will thereby compensate in a measure for the drop or rise in voltage as the load is varied. Probably one of the best voltage regulating machines was the inductor type alternator, which had a long magnetic path and very high density, in which the time element was six to eight times that of our present revolving-field type of generator, with a non-inductive load this alternator would probably regulate for voltage better than the revolving-field machine, but with an inductive load which required a much broader range in excitation the inductor alternator was not satisfactory. The reason this type of alternator was unsatisfactory in regulation was due to the fields requiring a very broad range in excitation, and with an inductive load the excitation was from two to three times that required by the revolving-field type of alternator, and with an automatic regulator which increases the field excitation according to the variation in load, it was a difficult matter to regulate this type of generator.

Second, in voltage regulation the exciter is also a very important factor. For example, if an exciter is designed at very high density the time element required to change the voltage from one point to another is so long that the voltage regulation may be materially affected, and in order to have the best combination for voltage regulation an alternator should require a range in excitation from no load to full load, with approximately 80 per cent power-factor, of a ratio of not more than one to two, *i.e.*, the normal no-load excitation required by a given alternator is 70 volts, and full 80 per cent power-factor load should not require more than 140 volts. Should the excitation voltage be

of any other value, *viz.*, 250 volts, the same ratio of excitation holds true.

In designing exciters to meet these conditions the densities of the exciters should be fairly low, especially in the fields. The exciter should also have a time element so that it will be responsive to changes in field excitation to the extent that the voltage will fall, by inserting an external resistance that will equal about three times the resistance of the field, from 125 volts to 25 volts in from six to eight seconds. The ideal exciter designed on these lines will also readily give at full field 165 volts

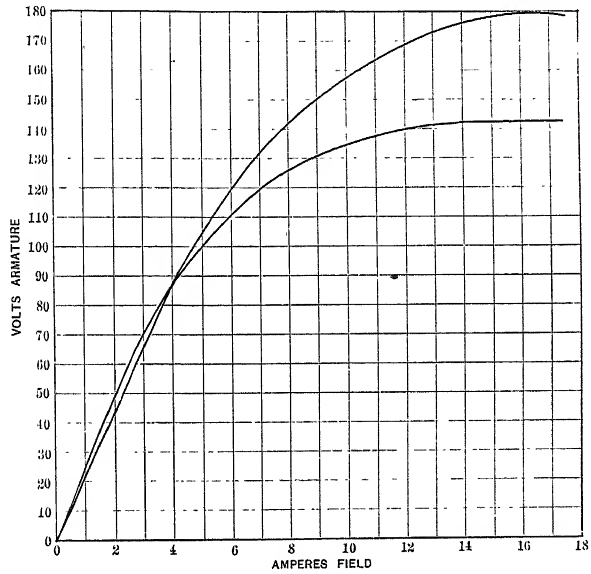


FIG. 1.—Saturation curve of direct-current exciters

and the increase in field current from 125 volts to 150 volts will not be over 50 per cent. This requirement on the exciter is necessary to take care of the heavy power load which most central stations are experiencing to-day; and frequently the excitation required on an alternator is 140 volts and in order to obtain the difference between about 100 volts and 140 volts quickly, it becomes necessary that the smaller the increase in field current from 125 volts to 150 volts the quicker the exciter will respond to the short-circuiting of the rheostat, to obtain the desired excitation required by the alternator.

Fig. 1 shows a curve giving the saturation on two given ex-

citers, one designed along the aforesaid lines, the other having high saturation with high density and a large increase in shunt field current between 125 and 150 volts. It can be readily seen that the latter exciter is not as suitable for good voltage regulation as the former exciter when an automatic regulator is used.

Before the automatic regulator was perfected the majority of exciters were designed with fairly high densities and very heavy series fields. In some cases the series field equaled 50 per cent of the total excitation of the exciter and with an exciter fully loaded it required a very large amount of resistance in the exciter field rheostat to vary the voltage of the exciter to any appreciable extent due to the series field supplying the large amount of excitation and holding up the voltage. In some cases where the series field excitation is about 50 per cent of the shunt field excitation the shunt field can be entirely broken under full load conditions and the voltage would not fall below 60 to 70 volts on 125-volt excitation, but since the adoption of the automatic regulator these conditions have been changed until now the series field excitation does not exceed 30 per cent of the total shunt excitation and oftentimes it is about 20 per cent, so that very good regulation is obtained by control of the shunt field rheostat.

Automatic Regulators

The only successful automatic voltage regulator known to the author is the one herein described, which was brought out about ten years ago and which has been used extensively ever since. This regulator operates on the theory of floating a pair of primary contacts by connecting one coil, which is known as the direct-current control magnet, to the exciter, bus bar and is graduated by mounting four springs on the lever connected to this control magnet and supported by a pivot at a proper distance so that this lever operates over the 100 per cent range in exciter voltage. These springs are so graduated as to pick up at a difference of 25 per cent in voltage; this keeps a constant torque on the contacts. The alternating-current element of the control magnet, connected to the alternator, is also balanced practically in the same manner except that a counterweight is used instead of springs. It is pivoted in such a manner that with a given voltage—say 110 volts—a balance is produced in which the contacts supported by the alternating-current lever and the contacts supported by the direct-current lever are at an

absolute balance, and with the core of the alternating-current magnet arranged to pull in one direction and the core of the direct-current magnet arranged to pull in the opposite direction this balance is produced in such a manner that the main contacts travel less than 1/32 in. (0.8 mm.) to obtain a range of 100 per cent increase in exciter voltage; and the opening at the main contacts in any condition is less than 0.01 in. (0.25 mm.). In addition to the two magnets described above there are also one or more relay magnets, the latter being differentially wound, so that with both windings energized the current is neutralized and the residual is reduced to a minimum and the operation of the relay is such that it can respond, without any time element, to changes required by the generator. The relay magnet

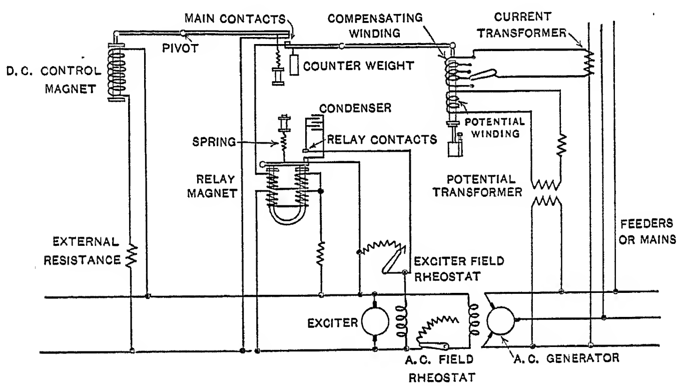


FIG. 2.—Connections for alternating-current or direct-current generators when exciters are used

is provided with one or more sets of contacts which are connected across the shunt circuit to the exciter field rheostat, the voltage being reduced first to 65 per cent below normal, at which point the rheostat is set before the regulator is cut into service. The alternating-current control magnet is also provided with current winding which is connected to a current transformer in some principal feeder so that the feeder can be overcompounded to take care of the drop in the copper between the central station and center of distribution.

An elementary diagram of the small automatic regulator is shown in Fig. 2. This is a small type of voltage regulator now designed for from one to four exciters depending upon their capacity, with as many alternators as it is desired to operate in

parallel. For exciters having larger capacity, elementary diagram Fig. 3 shows the same principle of regulator with the exception of the relay magnet which is a magnet designed with circular type flat coils but of the differential design, of which from two to twelve sets of relay contacts are employed, depending upon the size and characteristics of the exciters. The diagram in question shows the connections of two exciters, one set of relay contacts being connected to one exciter while the second exciter has its field rheostat divided up into two equal ohmic divisions having a set of contacts across each division so that the field discharge is taken up by both sets of contacts equally,

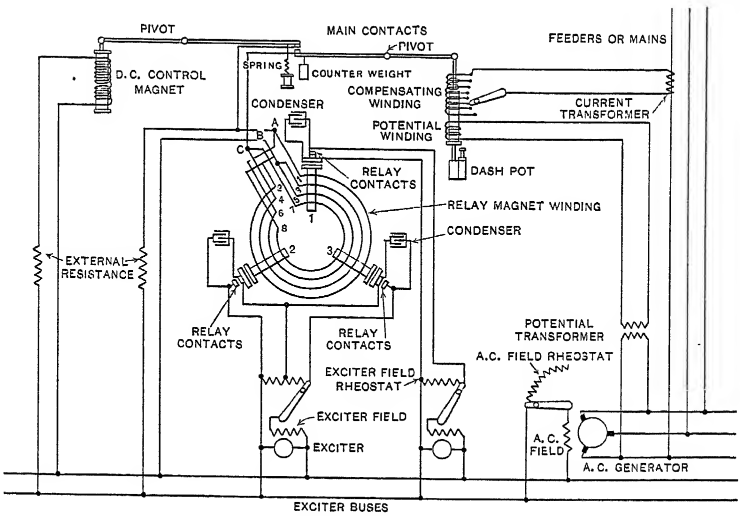


FIG. 3.—Connections of regulator for alternating-current or direct-current generator when exciters are used

and this method can be employed with the present design of voltage regulator up to 24 sets of contacts, having two sets of these relay coils in multiple controlled by one set of main contacts.

Regulation of Transmission Lines

The above regulators are designed to either hold flat bus bar voltage or compensate for non-inductive load through one current transformer. This arrangement does not compensate for an inductive load and in order to accomplish this result a line drop compensator is employed as shown in Fig. 4. Two current transformers are cross-connected in order to deliver the

proper amount of current to the line drop compensator which compensator is designed with a reactance coil and resistance coil; the resistance coil being for the non-inductive compensation and the reactance coil being for the inductive compensation. The current coil of the regulator is omitted with this connection and the compensation is secured by the current flowing either through the reactance or resistance coil of the compensator, and can be so adjusted that the voltage can be automatically controlled at the receiving end of a transmission line so that it

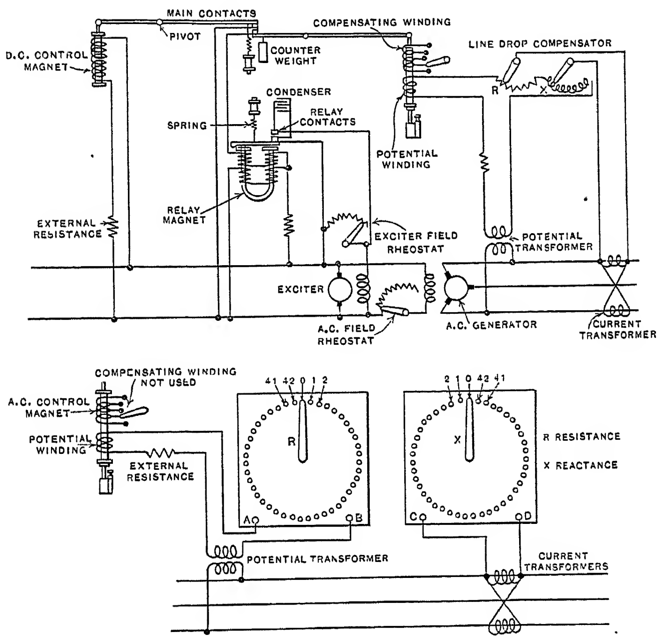


FIG. 4.—Connections of regulator for alternating-current generator using line drop compensator

can be absolutely constant under all conditions of load and power-factor, and will compensate up to 15 per cent above the no-load station voltage.

On long transmission lines where a large drop in voltage is experienced from heavy inductive loads it is generally conceded that the adoption of synchronous condensers is an advantage in increasing the output of the central station, and by the application of an automatic voltage regulator with a condenser of the proper size the installation can be made in some remote place

along the line where the condenser or regulator need very little attention and the condensers can be used for automatically compensating for line drop.

The same connections as employed in the alternating-current generator is applicable to synchronous condensers. The operation of the regulator is such that when the voltage tends to fall at the motor terminals due to heavy inductive load, the regulator will increase the excitation on the condenser and tend to deliver leading current to the line until this voltage is restored to normal, and as aforesaid, with the proper size of condenser the regulation at this point can be held absolutely constant by this method. In cases where synchronous motors are employed to drive railway generators the voltage regulator, with the addition of a line drop compensator, can be used to hold a given power-factor at this point, as it may be found from test on long transmission lines in which synchronous motor-generator sets are used that by holding 80 per cent leading power-factor the best line conditions are obtained, and in using the compensator and regulator this power-factor can be maintained at 80 per cent leading without any hand adjustment whatsoever.

Cycle of Operation

The cycle of operation of the ordinary voltage regulator is such that when the main contacts, with a given voltage on the generator, just begin to open the shunt circuit across the exciter field rheostat is opened and the exciter field rheostat reduced to a point that without the regulator in service the voltage on the alternator will be reduced to about 65 per cent below normal. By this adjustment it will be readily seen that the voltage regulator almost anticipates when the voltage of the alternator is about to change. Therefore by the adoption of the floating-contact system this regulator does not wait until the voltage actually changes before it operates, but it is continually operating due to the large percentage of resistance turned into the exciter field circuit; while with regulators of types which at a given voltage are stationary it requires change in voltage until these regulators operate in either one direction or the other. It can be readily seen that such a type of regulator would be unsatisfactory due to the time element in the regulator itself. This is primarily the reason why the present type of automatic voltage regulator has been so successful, as the regulator does not have to wait for the voltage to change but is operating all

the time owing to the fact that the voltage is tending to drop, but the regulator operating at a higher rate of vibration and intermittently short-circuiting and opening the shunt circuit across the exciter field rheostat makes the time element negligible.

Installations of Voltage Regulator

Connecticut River Power Co. As a practical illustration of the generator capacity for which the automatic voltage regulator

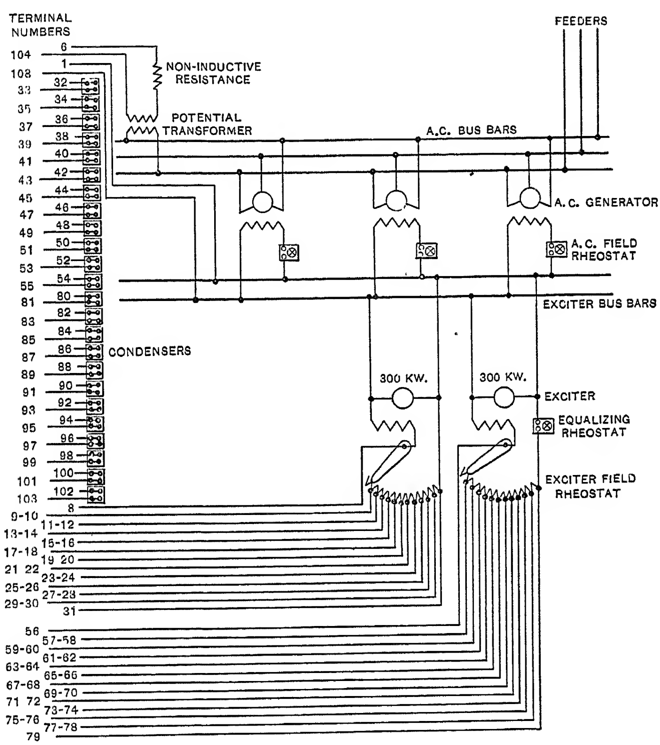


Fig. 5.—External connections of regulator with two exciters in parallel.

is now employed the plant of the Connecticut River Power Company may be cited, in which alternating-current generators aggregating 20,000 kw. are equipped with these regulators. The two 300-kw. 125-volt exciters are driven from vertical turbines and operate in parallel on one voltage regulator. The connections of this regulator are shown in Fig. 5, in which it will be noted that the 12 set of contacts are connected to each exciter

field rheostat. The rheostats are divided into 12 ohmic divisions, and it is impossible to see the slightest arc at the relay contacts. A line-drop compensator is also employed in this plant to compensate for the large inductive drop in the transmission line and the voltage is controlled automatically at the receiving end of the 66,000-volt, 60-mile (96.5 km.) transmission line.

Ontario Power Co. Another application of the automatic regulator is in the plant of the Ontario Power Company which delivers 30,000 kw. and contains two 375-kw. exciters equipped with two individual regulators of the eight-relay type. The exciter voltage is 250 and at times the regulators are operating

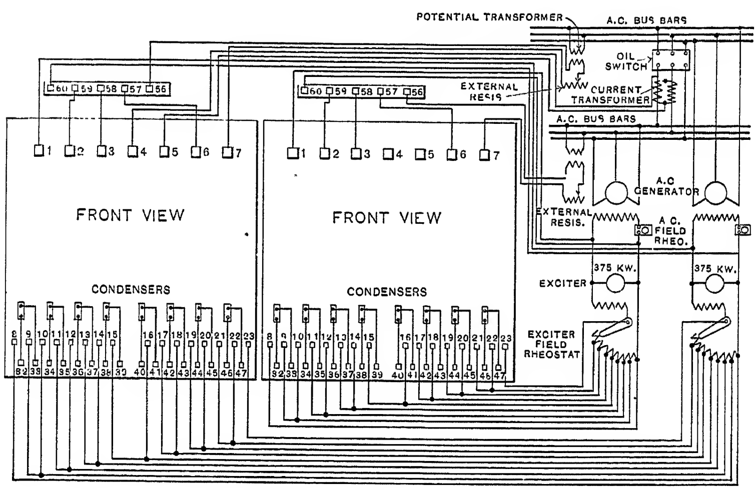


FIG. 6.—Connections of two regulators in parallel with two exciters in parallel

in parallel while at other times the station is sectionalized, each regulator being employed to control the voltage of one side of the station. When the regulators are operating in parallel it is necessary to install either a line-drop compensator between the regulators or to install a current transformer out of phase with the potential transformer as shown in Fig. 6, so that the cross currents which are liable to be produced by the two regulators operating in parallel can be overcome. When the stations are operating in parallel with a regulator in each station the reactance is usually sufficient so that the cross currents are not produced by the regulators, but on short transmission lines

trouble from cross currents with two generators operating in parallel with two regulators is liable to be encountered unless either of the above methods is used with one or the other of the regulators.

To further illustrate the flexibility of the large capacity voltage

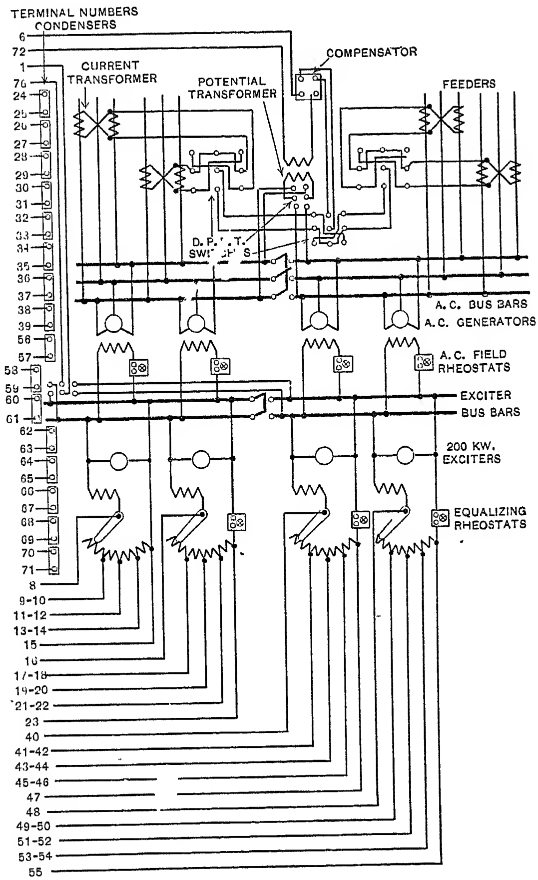


FIG. 7.—External connections of regulator for arrangement of four exciters

regulator, Fig. 7 shows a 16-relay regulator arranged for controlling four 8000-kw. alternators receiving excitation from four 200-kw. exciters. It will be noticed that the alternating-current as well as the direct-current bus bars are arranged for sectionalizing, so that the station can be operated with the regulator on either

set of busses, and a line-drop compensator is supplied so that it will control any one of four feeders. If the total station is operating in parallel and the regulator is controlling the principal feeder for compensation of line drop, the voltages on the remaining feeders at the center of distribution will agree very closely, but if the feeders are of variable lengths feeder regulators are employed so that absolutely constant voltage can be held at the receiving end, and it is only necessary for feeder regulators to compensate for the difference in voltage between the feeders. They do not have to take into consideration any fluctuating voltage such as might be experienced if the voltage regulator was not used.

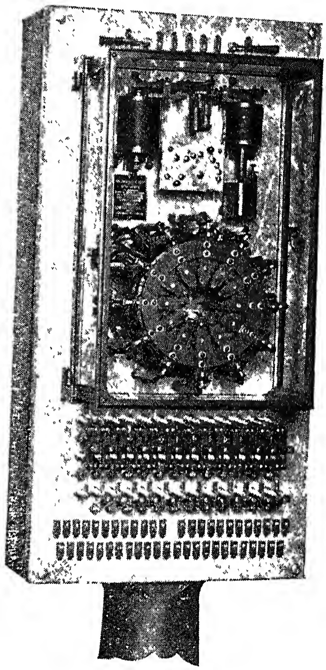


Fig. 8.—Regulator mounted on pedestal

New Method of Mounting

A new method of mounting this particular type of regulator is shown in Fig. 8, in which the voltage regulator is mounted on a cast iron pedestal. The external resistance used for the coils of these regulators is enclosed in the pedestal, and the pedestal being hollow the wiring is all concealed.

With any of the regulators herein described it is never necessary to interrupt the voltage in case of throwing different exciters or alternators in parallel, nor should the regulator be cut out of service for any cause whatsoever. For example, if the voltage regulator is connected to two exciters and two alternators and the load becomes such that it is necessary to start up the third alternator and exciter; the exciter is first brought up to the proper voltage and paralleled; the voltage regulator is then connected to the third exciter; the resistance turned into the exciter field to a point that will reduce it to 65 per cent below normal, and the load between the exciters is equalized by a small resistance placed in series with the exciter which tends to take the greater portion of the load when both the exciter field rheo-

stats are short circuited by the regulator. The alternator is then synchronized and placed in parallel and no interruption in service is occasioned. Should it be necessary to take out one alternator and exciter it is first desirable to transfer the load from the generator which it is desired to shut down. The main switches on the generator are then tripped out and the load is transferred from the exciter by the use of an equalizing rheostat in the same manner and the main exciter switch is opened, after which the contacts corresponding to this exciter are cut out. It will therefore readily be seen that the voltage regulator can be employed 24 hours a day without any interruption whatsoever from either paralleling or cutting in and out different machines or feeders.

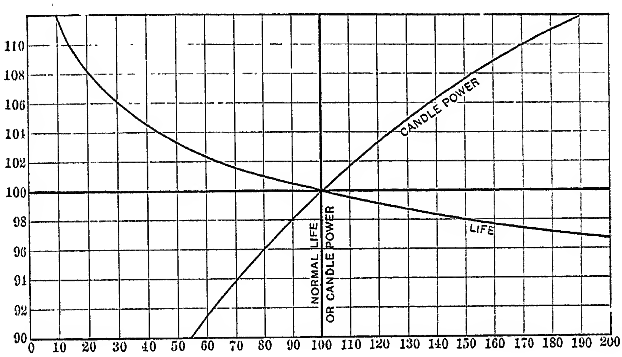


FIG. 9.—Relation of light and candle power of incandescent lamps to voltage regulation

VOLTAGE REGULATION OF DIRECT-CURRENT GENERATORS

The regulation of direct-current generators has probably not been as important as the regulation of alternating-current generators because direct current has been superseded for central station work by alternating-current, due to a number of well-known reasons. For isolated work, such as office building, apartment houses, and hotels, with the present practice of installing elevators and lights on the same circuit, is necessary to have some means of automatic regulation for the direct-current generator. A large variation in voltage due to starting the elevators will be experienced and cause a loss in the candle-power of the lamps which not only decreases their brilliancy but shortens their life to a considerable extent. To briefly

show the variation in life and candle-power of an incandescent lamp which is subject to voltage variation the curves of Fig. 9 are given, showing that if the voltage drops 2 per cent it reduces the candle-power of the lamp to 89 per cent of normal, and a 2 per cent increase in voltage reduces the life to 65 per cent of normal. It can readily be seen that the more closely the voltage is maintained the longer will be the life of the lamp. This holds true with alternating-current lighting as well as direct-current lighting.

The principle of regulation of the direct-current generator is shown in Fig. 10. The voltage regulator is designed with one main control magnet which is connected permanently to the bus bars of the direct-current generators, and has one movable and one stationary core. These cores at a given flux are balanced

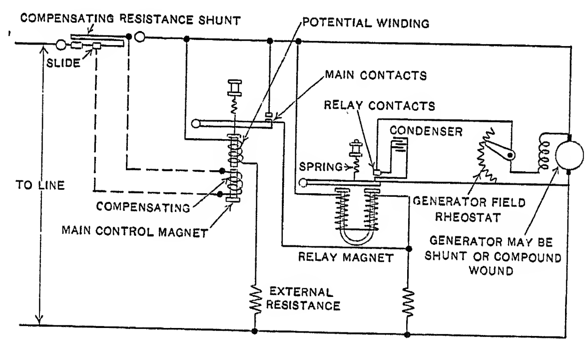


FIG. 10.—Connections of regulator for direct-current generator

by the spring, calibrated so as to float them at a certain voltage. The lever supporting the core and spring is equipped with a pair of contacts which operates a relay. For simplicity this relay is shown series wound. The main contacts open and close the winding of the relay which overpowers the spring supporting the armature which carries the relay contacts. The relay contacts are connected across the shunt field rheostat, which is first turned to give about 35 per cent of the normal voltage which it is desired to maintain, so that when the relay contacts are closed the generator voltage tends to rise until it reaches normal value. The main contacts are opened which in turn open the relay contacts which tends to reduce the voltage 35 per cent below normal, but this does not actually happen as the main contacts being set for a given voltage and operating

at a very high rate of vibration the voltage is maintained at the predetermined value and is constant under all conditions of load and speed changes. This was one of the first successful voltage regulators for direct-current generators but it was limited in capacity to one relay. As most direct-current generator installations require two or more generators of from 100 to 200 kw. capacity each, a single-relay regulator was found to be too small to handle the field discharge of these large generators. It was therefore necessary to resort to the multiple relay type of regulator which operates on the same principles but which has a number of relays controlled by one set of main contacts. The

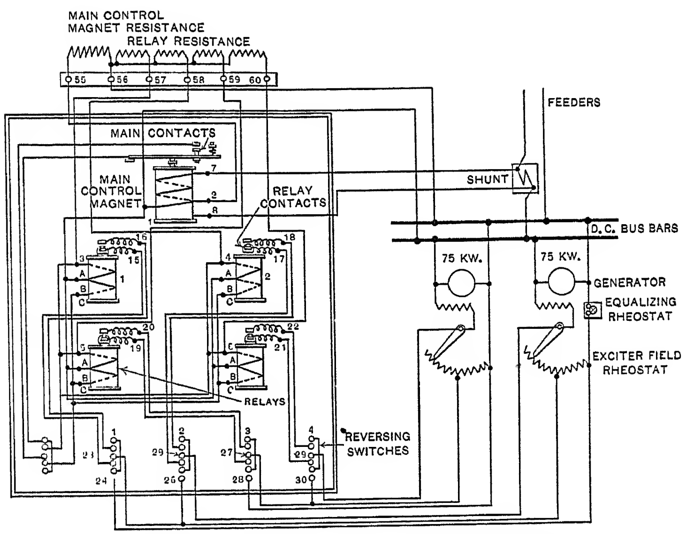


FIG. 11.—Connection of regulator for two direct current generators in parallel

multiple relay type of direct-current regulator differs slightly from the alternating-current regulator in the design of the relays which are differentially wound with parallel conductors so as to neutralize the self-induction of the coils thus eliminating the sparking at the main contacts. It is impossible to place a condenser section across the main contacts owing to the condenser discharge causing the main contacts to stick, the break not being sufficient to allow the condenser to discharge properly; and if the break is large enough to allow this discharge the regulation will be affected. Condensers are placed across the relay contacts to absorb the arc as these contacts are usually set

about 1/32 in. (0.8 mm.) apart. The connections to the generator field rheostat when multiple relays are used are shown in Fig. 11, in which it will be noted that there are four relays in multiple operating with one set of main contacts. They are operating on two 75-kw. generators having the resistance of each generator divided into two equal ohmic divisions. For the compensation of line drop a shunt is used in the principal lighting feeder which is connected to the current winding of the main control magnet which opposes the potential winding. As the current increases in the shunt the potential winding is opposed

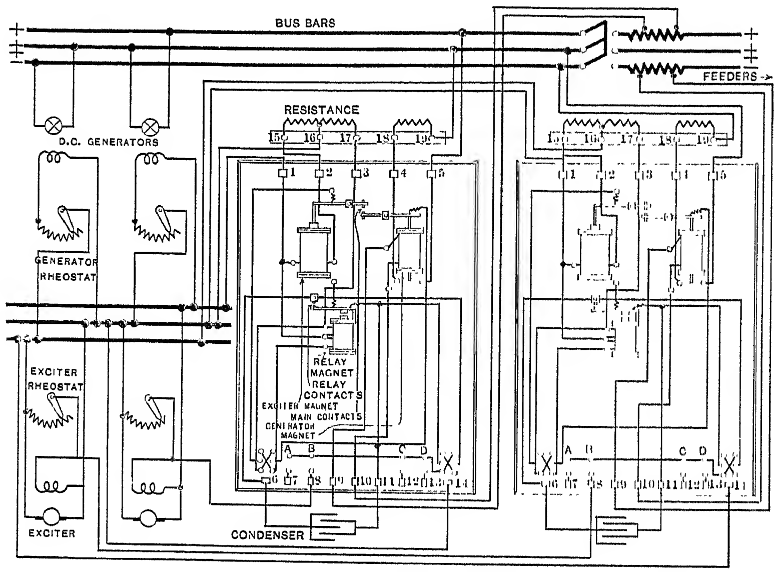


FIG. 12.—Two regulators on a three-wire direct-current system using exciters

by the current winding and the spring overpowers the core and raises the voltage so that it is possible to compensate about 15 per cent drop in feeder circuits. Another method of regulating direct-current generators is to employ the alternating type of floating contact regulator and separately excite the direct-current generators from an exciter. The direct-current generator in this case virtually becomes an alternating type of generator as far as the principle of regulation is concerned. For Edison three-wire systems, two regulators and two exciters are employed as shown in Fig. 12. For large direct-current installations the latter arrangement is very satisfactory as the

current to be handled by the regulators is very small and they can also be arranged for overcompounding for line drop by the shunt described above—the current winding opposing the potential winding of each regulator. The exciters for the main generators operate in series the same as the generators themselves.

Special Regulators

There are numerous applications of voltage regulators which no attempt will be made to describe in this paper, such as regulating alternating-current systems where a storage battery is floating on the exciter bus. The method employed here is to use a booster with the voltage regulator to either boost or buck the exciter voltage to the proper amount. Special regulators are also in use for constant-current work, flywheel equalizing sets, and many other special applications.

There is one special appliance in addition to voltage regulators which should be mentioned, and that is an automatic device to be placed on an alternating-current system where heavy short circuits are encountered. If the voltage regulator is employed and a short circuit is experienced—the action of the regulator will tend to hold the voltage up and therefore give the exciter full field. Often in hydroelectric installations when this happens the water wheel gates are wide open—full excitation is supplied to the exciters and generators—and if the short circuit is suddenly relieved the voltage is likely to rise above normal value before the excitation can be reduced on the generators and exciters. The time required to reduce this excitation is the time taken by the generators and exciters to demagnetize their fields between maximum full field voltage and the voltage corresponding to the normal load excitation, which may be from two to six seconds. This is augmented by the time required for the water wheels to reduce the speed to normal. This can be overcome by placing overload and high-voltage relays in the transmission lines set so that should the current increase to a given value the relays will trip, open the connections to the regulator and reduce the voltage to a certain value (to be determined by the operating engineer) and after the short circuit is burned off and the current become normal again the relays will close and the regulator will automatically be returned to service.

While the above device is not necessary in ordinary central stations it is a very important factor in large hydroelectric installations.

DISCUSSION ON "VOLTAGE REGULATION OF GENERATORS", SCHENECTADY, FEBRUARY 16, 1911.

H. G. Reist: I would recommend this paper to the careful consideration of engineers who design and operate stations, and call attention to the fact that the use of regulators in stations allows us to build generators having inherent regulation not as good as has been thought desirable in the past. The reason for desiring generators having poorer regulation was fully discussed this morning but I might repeat that it is desirable to have such machines to avoid excessive currents and thus endanger generators and other station apparatus in case of a short-circuit on the system. Reducing the flow of currents during short-circuits is of advantage in every respect except that it spoils the regulation of the system. In large systems this is usually of no importance and in small ones the potential can readily be maintained by means of regulators.

Carl J. Fechheimer: That poor regulation rather than close regulation of alternators is really desirable in a great many cases is becoming more and more the opinion of engineers. This applies especially to high-speed generators, particularly those of the turbo type, in which the size of machine is almost entirely determined by rotor heating and stresses, it being understood that these generators supply current for induction motors, so that the load of the system is inductive and the power factor rather low.

It is usually considered to be essential at the present time for generators to maintain their voltage at 25 per cent overload, 80 per cent power factor. It may be shown that the ratio of the maximum ampere turns in the field winding to the ampere turns in the stator at full load is nearly fixed for a definite regulation and for the amount of overload which the generator should carry at the power factor of the circuit, and still maintain its voltage. From this it will be seen that if the voltage regulation be very close it results in a rather large rotor or else great heating in the rotor; hence, from this point of view we can materially gain if we sacrifice regulation slightly, a voltage regulator being used.

As the size of units and transmission systems increase in their output, close voltage regulation is often found to be unnecessary, as the changes in load on the system are very slight compared with the combined output of the units supplying power to the system. In such cases the change in voltage is hardly sufficient to detect a perceptible change in the illumination produced by the lights on the circuits.

From another viewpoint, close voltage regulation would be undesirable as this also implies that in case of short circuit the damage which may be done to the end connections of the generators and to other apparatus may be considerable.

There is, however, one serious objection to having poor

inherent regulation when a regulator is used and that is, if the currents of the various phases of the generator be unbalanced, the voltages will be correspondingly unbalanced, with the result that the lights will burn dimly on one phase and brightly on another. While this may be remedied with the use of compensators, it is only done by complications which would be unnecessary were the generator to have closer regulation.

It is my opinion that reasonably good regulation is very desirable in small generators (up to 500 kilovolt-amperes) and that it becomes of less importance as the size of the generator is increased. In a 5000-kilovolt-ampere alternator, a regulation of 15 per cent at 100 per cent power factor and 30 per cent at 80 per cent power factor should be sufficiently close for nearly all cases.

E. F. Alexanderson: The Tirrill regulator is usually thought of as a voltage regulator, but I wish to call attention to the varied possibilities for its application. Ordinarily the regulator is adjusted so as to maintain constancy of a certain electric quantity, for instance, voltage, current, or combination of the two. This is done by balancing the attraction of the regulating magnet against a counter weight or spring pressure. In many cases, however, it is desired not to maintain the constancy of the voltage or current, but to regulate the relative magnitude of two electrical quantities, for instance, to regulate the relation of wattless current to energy current; in other words, automatic regulation of the power factor by a synchronous machine, or maintaining equality of the two voltages in a three wire system by a balancer set. In such a case the regulating magnet is not balanced against a spring, but equilibrium is established by the equal and opposite attraction of two magnets, or by the action between two magnets becoming zero due to the currents being out of phase.

There are numerous variations of this principle, and, in general, it is only worth while remembering that the regulator is an instrument which lends itself with only slight or no modification to the automatic regulation of almost any electrical quantity that can be measured.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

THE DIRECTION OF ROTATION IN ALTERNATING-CURRENT VECTOR DIAGRAMS

BY ERNST J. BERG

The object of this brief is to present the writer's views on the proper vector representation of alternating-current phenomena. The question is attacked from the point of view of the teacher of alternating currents to undergraduate students.

In electrical engineering are treated chiefly the phenomena which are caused by alternating currents and e.m.fs. The currents as well as the e.m.fs. are periodic functions of time; as the time changes, the instantaneous values of these functions also change. Thus, it seems rational to consider time as the independent variable in illustrating such phenomena.

In representing them graphically, several methods are conceivable, but it seems to the writer that the following two are simplest and indeed the only two which by their simplicity can be considered when dealing, as is always done in practice, with phenomena involving multiphase work and more especially multiphase work with distorted waves.

It is realized that in the case of single-phase circuits with sine waves of current and e.m.fs. other methods may seem as simple, and by many, simpler.

First. Rectangular coördinate system with time as abscissas and instantaneous values of current and e.m.f. as ordinates.

This is illustrated in Fig. 1, which gives the changes in current in a three-phase system.

Second. Polar coördinate system. In this case the independent variable—the time in represented by the angle ϕ, and the instantaneous values of the currents by the radii vectors. The result in case of a sine wave is the polar curve, the circle.

Thus, in a symmetrical three-phase system, the values of the currents in the three lines is found by reference to the three circles in Fig. 2.

In this particular diagram, zero time is represented by the position of vector $O\,A$.

The values of the currents in the three lines at that time are expressed by:

In line $I + O\,A$.
In line $II - O\,B$.
In line $III - O\,B$.

It is at once evident to the student that the current that flows out over line *I* is returned partly by line *II*, and partly by line *III*. In this case, one-half of the current returns over line *II*, the other over line *III*.

The student sees that it is the *same current*; sees that the three instantaneous currents are in phase.

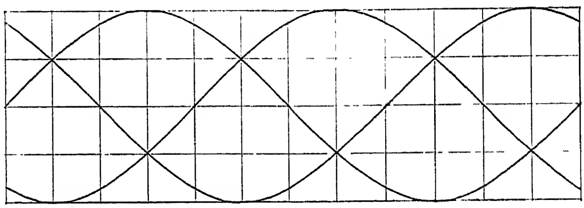


FIG. 1

The currents at time ϕ are:

In line $I + O\,C$.
In line $II \quad O$.
In line $III - O\,D$.

The student sees that at that particular time, line *II* carries no current; all current that leaves line *I*, returns in line *III*. He sees that in a four-wire three-phase system with balanced load, there is no current in the neutral line, all current going out in one line returns in one or both of the other main lines.

The diagram, if referred to the e.m.fs. instead of currents, shows that the common connection is at neutral potential since at all instances the positive voltage is as great as the negative.

In the case of distorted waves, and all waves in actual engineering are distorted, the diagram lends itself with equal facility. In Fig. 3 is given the counter e.m.f. of a transformer corresponding to a sine wave of exciting current, a wave approximately

obtained between one of the lines and the neutral of Y-connected transformers in the three-phase system.

This wave contains a large triple frequency component and some components of higher frequency.

The instantaneous values of the three currents at any one time is obtained as readily as in the first case. It is seen here that the common connection has not neutral voltage. Thus, there is an active e.m.f. generated between the "neutral" and the three lines as returns.

With such distorted wave, a considerable current would flow to the common connection, if such were established, even if the three-phase load was balanced.

It is readily shown that any other odd harmonics except the third and its multiples do not cause a pulsating voltage between

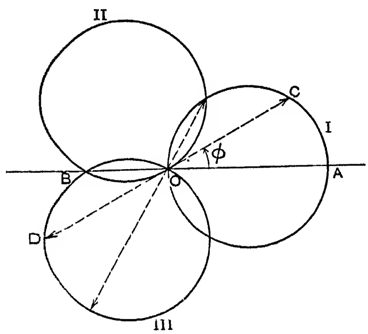


FIG. 2

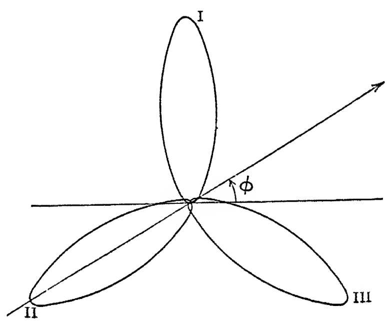


FIG. 3

the neutral and the outside lines, the algebraic sum of the three e.m.fs. are at all lines zero. This is illustrated in Fig. 4 which shows the distorted wave of the fundamental and a fifth harmonic of one-half the intensity of that of the fundamental.

The polar coördinate system has also another great advantage in determination of the effective values of a distorted wave. It is well known that the square of the effective value is obtained by dividing the area as obtained by planimeter by $\frac{\pi}{2}$.

In teaching alternating current phenomena, it is in the writer's opinion absolutely necessary to dwell a long time on the instantaneous variations. His experience is that by this method and this method only can the student get a clear insight of the theory. It seems nearly useless to teach electrical engineering

by referring at once to vectors of effective currents and e.m.fs. only. These should be introduced first after the students have obtained thorough knowledge of the instantaneous changes.

The writer is frank to confess that he has failed to see a simple application of the so-called crank diagram in these cases.

The crank diagram, to be sure, lends itself readily to simple single-phase diagrams with sine wave of currents and e.m.fs.; that is, to circuits and conditions which are not found in practice, it lends itself only to very expert mathematicians in case of multiple phase circuits with distorted wave shapes.

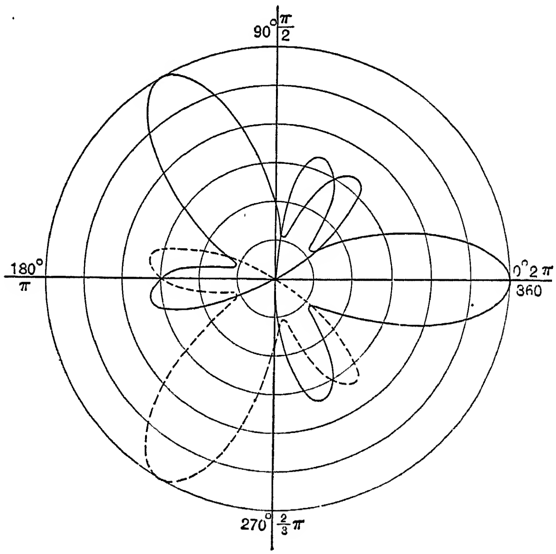


FIG. 4

It seems unlikely that sufficient time can be found in undergraduate work to explain the necessary mathematics. It seems also that the diagrams become so complex as to be almost beyond interpretation.

If it is agreed that the polar-coördinate system with time as independent variable, is preferable, then the whole controversy seems to me settled. It is not a question of direction of rotation; the rotation is counter clockwise in any case. In the polar coördinate system, time rotates counter clockwise. In the crank diagram the e.m.fs. or currents are made to rotate counter clockwise.

The adoption of the polar diagram settles the complex expression of current, impedance, etc.

$$I = i + j\, i_1 \text{ represents a lagging current}$$

$$r - j\, x \text{ represents an impedance.}$$

To sum up, it is the writer's opinion that the indirect representation, the polar circle diagram, Steinmetz' method, or whatever the representation is called by various writers, is preferable to the so-called direct representation, or the crank diagram, for the following reasons:

It is a simple application of polar coördinates, whereas the "direct representation" is a mixture of the polar and the rectangular coördinate systems, a system which hardly appeals to the mathematician.

The indirect representation has the great advantage that the dependent variable is read directly as the intercept on the rotating vector, whereas, with the other method, it requires a projection and, therefore, an added mental and mechanical operation. This advantage is, of course, much more noticeable when two or more variables are used, since it is far easier to read two or more intercepts on a single line than to construct the projections.

All engineering students are familiar with this representation of interception of a rotating line from their work with the Zeuner diagrams so that it is at once understood by them.

A paper presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, February 16, 1911.

CONVENTIONS IN CLOCK-DIAGRAM REPRESENTATION

BY W. S. FRANKLIN

Everyone understands the vector representation of simple alternating electromotive forces and currents, and therefore a skeleton outline will be sufficient to call to mind the connection between: (*a*) the two styles of clock-diagram, and (*b*) the usual geometrical conventions in trigonometry and the usual conventions governing the geometrical interpretations of complex quantity in algebraic analysis.

Definition. A harmonic electromotive force (or current) is an electromotive force (or current) which varies as the sine or cosine of an uniformly increasing angle. This may be expressed in accepted notation by the familiar equation:

$$e = E \sin \omega t \tag{1}$$

In the geometric representation of harmonic electromotive forces and currents two styles of clock-diagram are in use. These we will designate as *diagram A*, and *diagram B*.

CONCERNING DIAGRAM *A*

1. The customary representation of a positive angle θ is shown in Fig. 1.

2. The customary representation of sin θ and cos θ is shown in Fig. 2.

3. The customary representation of a uniformly increasing angle is shown in Fig. 3.

4. The representation of a harmonic electromotive force in conformity with Figs. 1, 2 and 3 is shown in Fig. 4.

5. The representation of a lagging current in conformity with Fig. 4 is shown in Fig. 5.

6. In Fig. 5 the leading vector E is the leading quantity in time phase.

7. *The Addition Theorem.* The most important thing in the vector representation of harmonic electromotive forces (or currents) is what may be called the addition theorem. Stated in purely geometrical terms this theorem is that the sum of the projections of the two sides of a parallelogram is equal to the projection of the diagonal. A simple example of the addition theorem is shown in Fig. 6.

NOTE:—All diagrams show positive values according to established conventions.

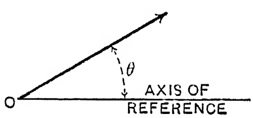


FIG. 1

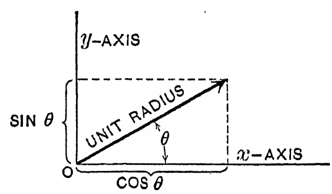


FIG. 2

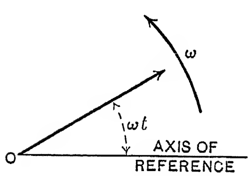


FIG. 3

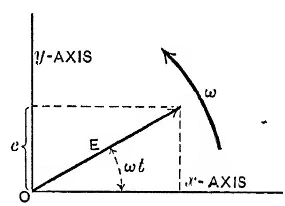


FIG. 4

CONCERNING DIAGRAM *B*

8. The customary representation of polar coördinates r and θ is shown in Fig. 7.

9. The polar-coördinate representation of a harmonic electromotive force $e = E \sin \omega t$ is shown in Fig. 8. For the sake of visualizing the function e, it is represented in Fig. 8 as the projection of a fixed E-vector upon the rotating radius vector. In this way it has come about that the fixed E-vector in Fig. 8 is thought of as representing the given harmonic electromotive force in substantially the same way that the rotating E-vector in Fig. 4 represents a given harmonic electromotive force.

10. The representation of a lagging current in conformity with Fig. 8 is shown in Fig. 9.

11. In Fig. 9 the leading vector in space is the lagging quantity in time phase.

12. *The Addition Theorem.* Those who prefer clock-diagram B seem to emphasize the polar-coördinate idea and to minimize the projection idea. A certain loss of simplicity is involved in this emphasis as may be shown most strikingly by stating the all-important addition theorem in terms of circular loci: The sum of the portions of the radius vector which are cut off by two

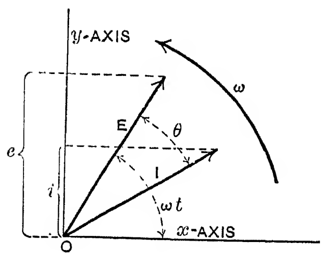


FIG. 5

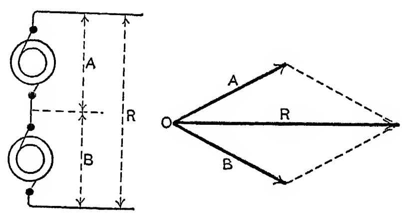


FIG. 6

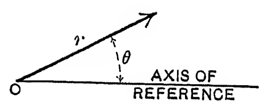


FIG. 7

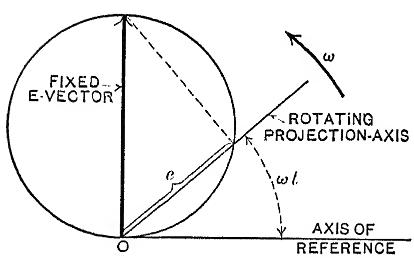


FIG. 8

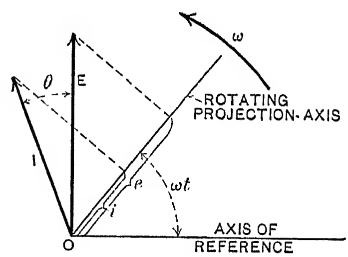


FIG. 9

given circles passing through the polar origin is equal to the portion of the radius vector which is cut off by a third circle whose diameter is the diagonal of the parallelogram constructed on the diameters of the given circles as sides.

IMPORTANCE OF THE IDEA OF PROJECTION

There is no question as to the fundamental importance and simplicity of the idea of projection in the representation of the sine and cosine in trigonometry, and the importance and sim-

plicity of the idea of projection in the representation of any sine or cosine function is equally beyond question.

If the idea of projection is to be used in the most powerful way, the projection axis must be looked upon in a sense as a reference axis and it should be stationary; at least this is the conventional point of view in nearly every case in which sine or cosine functions are used in geometry or physics.

The idea of projection on fixed axis of reference is the basis of the conventional geometrical and physical interpretation of complex quantity. In simple alternating-current theory this may be shown in outline as follows: Consider the differential equation

$$E\,\epsilon^{jwt} = R\,i + L\,\frac{d\,i}{d\,t} \tag{2}$$

The important singular solution of this equation upon which the whole of the elementary theory of alternating currents is based is:

$$i = I\,\epsilon^{jwt} \tag{3}$$

Now according to established conventions this equation represents a constant-length vector rotating at angular velocity ω in a counter-clockwise direction. Resolving equation (**3**) into real and imaginary parts, we have

$$i = I \cos \omega\, t + i\, I \sin \omega\, t \tag{4}$$

Either component of this equation is a physical solution of equation (**2**), and these algebraic components of equation (**3**) correspond exactly, according to widely accepted conventions, to the geometric components of the rotating I-vector in a clock diagram like Fig. 4.

The Difference Between Diagrams A and B

Let us call diagram A with all of its accompanying ideas and conventions a *group*, and likewise diagram B. Now if the difference between two such groups depends upon one item, then this difference can be expressed in as many ways as corresponding items of groups A and B can be combined. Such is the *group theory* explanation of this and of most other long-drawn-out and inconsequential discussions among men. Thus may the

most recent and the most recondite development of pure mathematics be *applied!*

The fact is that diagram B differs from diagram A in that diagram B does violence to the established convention as to the positive direction of rotation. This is a fact. Unfortunately it can be stated in a great variety of ways, but it is a fact. Some may object, for, behold! the direction of rotation in Figs. 4 and 8 is the same! To such we declare, again, the fact, as above stated. It is a question of what moves, or, rather, of what is supposed to move. Indeed (and it is with a profound appreciation of the convincing power of scientific elegance among men that I mention a second modernism in pure science) it is a principle of relativity. If London is east of New York, why, then New York is west of London. And so we see the most recent and the most recondite development of physical theory, the theory of relativity, *applied!*

Discussion on "The Direction of Rotation in Alternating Current Vector Diagrams", "Conventions in Clock-Diagram Representation." Schenectady, February 16, 1911.

G. L. Hoxie (by letter): Mr. Berg's paper presents very clearly certain undoubtedly valuable features of the polar-diagram-representation of alternating quantities. This kind of diagram has been made familiar to us in this country mainly by the joint writings of Messrs. Berg and Steinmetz. It seems to me, however, that the question is not so much that of selecting a " proper " method of graphical representation, to the exclusion of other methods, as a question of selecting for a given case the method best adapted to it.

In the teaching of alternating currents to undergraduates, it has been my experience that some students will pick up an idea in one way and some in another, and that the teacher should present the same matter from as many angles as possible, and with almost endless repetitions. It would seem that the majority of students find the rectangular coördinate system most readily grasped. A few others will find that the polar system, illustrated in Figs. 2, 3 and 4, seems simpler. There will also be some students who will understand the rectangular diagram (Fig. 1), first, and thereby be helped to grasp the meaning of the polar diagram, which latter they will thereafter prefer.

All of this however has to do with the *explaining* or *describing*, of phenomena. As Mr. Berg very truly says, the teacher must dwell a long time on instantaneous variations, and the student gets his first clear understanding from the rectangular and polar systems described in the paper. The idea of rotating and projecting a vector, particularly when the length of the vector is not constant, is unquestionably more difficult.

After the student has been thoroughly grounded on the general features of the alternating circuit, so that he understands pretty well what we mean when we speak of leading and lagging currents, how currents combine in three phase circuits, and in various unbalanced circuits; or in short when he has a good general *qualitative* knowledge, it is necessary to introduce him to some tools to use in solving problems. From this point I believe the rectangular and polar diagrams should mainly be dropped, being occasionally introduced in connection with some particular problem to refresh the comprehension of instantaneous conditions.

The notion of vectors, the idea of projection, and the complex quantity, should be explained. The analytical and graphical conventions of the complex quantity should be learned, and the effective values of currents and electromotive forces (considered thereafter rather arbitrarily as directed quantities), should then mainly be dealt with. Usually, at first, solutions should be graphical, carefully making diagrams to scale—and later on analytical, making use of the complex quantity. The conven-

tions that were used some years ago by Dr. Kennelly, in an Institute paper dealing with hyperbolic functions, seem to me the best ones to follow.

I entirely agree with Mr. Berg as to the desirability of cutting out complex mathematics. If any mathematics looks complex to Mr. Berg, it is not likely that many Institute members will care to spend much time on it.

Charles P. Steinmetz (by letter): It is regrettable that two different representations of alternating vectors exist, of which the one appears like the mirror image of the other. The difficulty extends to the symbolic representation of the vectors, as in the one, the time diagram, inductive impedance is represented by $Z = r - j\,x$, and in the other, the crank diagram, by $Z = r + j\,x$.

It would be very desirable to reach an agreement on vector notation, but this does not seem feasible, due to the apparent impossibility of getting an intelligent decision on the subject, as many of the men who discuss the subject and write on it, are familiar with one representation only, but never have taken the trouble to understand the other representation, but, since it appears like the image of the notation familiar to them, merely assume it to be rotation in opposite direction. All the briefs written on the matter do not appear to change the condition, since they do not seem to be read. It appears hardly fair and reasonable to accept the judgment of somebody, who has not taken the trouble to understand the subject, on which he judges.

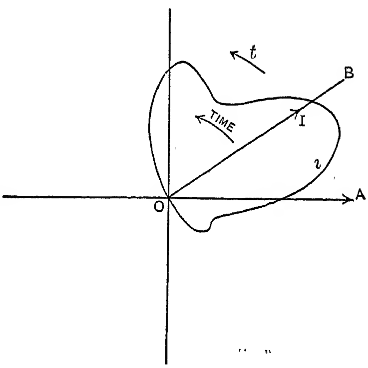


FIG. 1

To some extent, an illustration hereof is the title of the Institute discussion " On Vector Rotation ", though it is not a question of rotation at all, as both methods rotate in the same direction, counter-clockwise, but a question of *notation*, that is, of the meaning of the vector.

If the difference in the two representations were merely the difference in the direction of rotation, the symbolic representation would be the same: since $+j$ mathematically represents an angle 90 degrees behind $+1$, $+j$ in the crank diagram represents a vector, which has moved 90 degrees farther, that is, is ahead in rotation, or leading the vector $+1$, regardless whether the direction of rotation is counter-clockwise or clockwise, and in the time diagram, $+j$ represents a vector of a phase, which is 90 degrees later in time, than $+1$, that is, lags by 90 degrees, regardless again, whether the rotation is clockwise or counter-clockwise. The mere fact, that the symbolic denotations of the two representations are different, should make it evident to anybody, that

the difference is not a mere difference in the direction of rotation, but a difference in the meaning of the vector.

In my opinion, the question is, whether we should have one vector representation, or two different forms of vector repre-

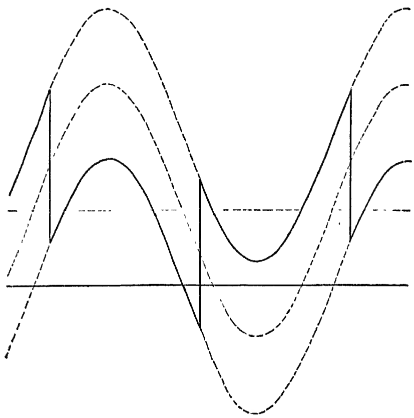


FIG. 2

sentations. Both, the crank diagram and the time diagram, represent sine waves about equally well. The crank diagram, however, is practically limited to the representation of sine waves, while the time diagram, which is nothing but the standard system of polar coordinates of analytic geome ry, can also represent complex waves and even non-periodic phenomena, as they exist in alternating current circuits as electrical transients. As long as the electrical engineer will have to deal with distorted waves and with electrical transients, in their graphic representation the polar coördinates, that is, the time diagram will by necessity be used, and the question then is, whether the same diagram should also be used for sine waves, or whether in the crank diagram the students shall be made to learn a second form of representation.

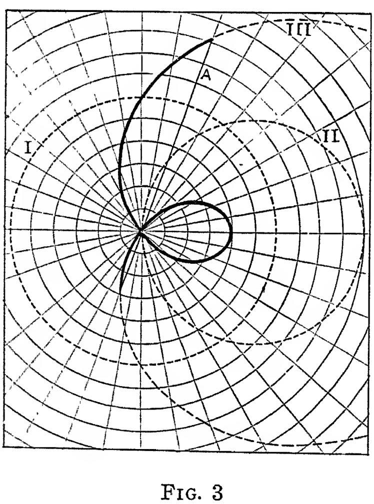


FIG. 3

An illustration of the representation of a distorted wave by the time diagram is shown in Fig. 5 of my discussion of " Vector

Power in Alternating Current Circuits", in the November PROCEEDINGS 1910 of the A. I. E. E., which is reproduced here as Fig. 1. The polar curve shows 5 extrema (maxima and minima) and thereby demonstrates the preponderance of the 5th harmonic.

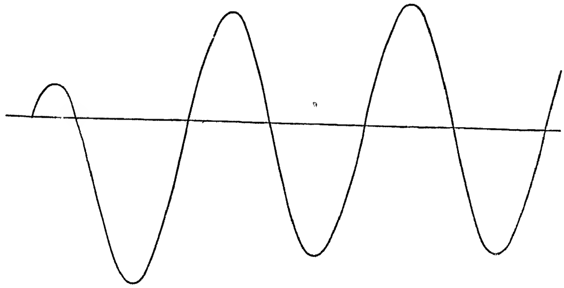


FIG. 4

Figs. 2 and 3 show the current in the armature conductors of a synchronous converter, Fig. 2 in rectangular coördinates, Fig. 3 in polar coördinates. Fig. 3 shows by the area of the curve the heating effect of the current, and demonstrates the great increase of the $i^2 r$ loss with increasing shift of the phase, that is, increasing shift of the line A from the vertical. Curve I gives the direct current circle, curve II the alternating current circle, and curve III the resultant, from which the line A cuts out the actual current, which latter is shown in heavy drawn line.

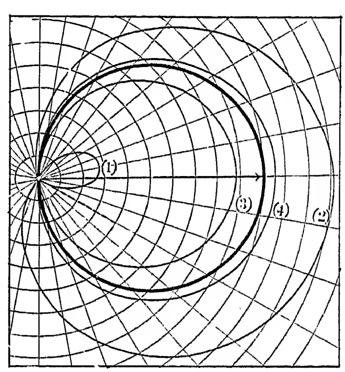


FIG. 5

Figs. 4 and 5 show the starting transient of an alternating current in an inductive circuit, in rectangular and in polar coordinates. Fig. 5 is interesting in illustrating the apparent phase advance of the current waves (2) and (4), which represents the power increase corresponding to the storage of energy in the magnetic field.

Louis F. Blume (by letter): When either the clock diagram or polar coördinates are employed to graphically represent alternating current phenomena, two ideas are involved. First—a characteristic which represents the alternating sine wave, and second—a mechanism by which the characteristic is subjected to a definite action. In the clock diagram the mechanism is the rectangular system of coördinates and the characteristic the straight line. In the polar coördinate system the mechanism is

the rotating radius vector and the characteristic is a circle. In the clock diagram the vector when subjected to the idea of rotation and projection will completely represent an alternating sine wave, and in the polar coördinate system the circle when subjected to the idea of the intercept of a rotating radius vector will completely represent an alternating sine wave.

But, by the employment of a circle for representing graphically an alternating sine wave, the polar coördinate system does not result in a vector representation. This fact is excellently shown in Dr. Berg's paper, which compares the polar system with the rectangular coördinate system. It should be noted that Figs. 2, 3 and 4 in this paper cannot be called vector diagrams any more than Fig. 1 in the same paper can be called a vector diagram.

In describing the polar coördinate system of rotation, Dr. Steinmetz in *Alternating Current Phenomena*, page 20, gives the following:

"The characteristic circle of the alternating sine wave is determined by the length of its diameter—the intensity of the wave; and by the amplitude of the diameter—the phase of the wave.

"Hence, whenever the integral value of the wave is considered alone and not the instantaneous values, the characteristic circle may be omitted altogether, and the wave represented in intensity and in phase by the diameter of the characteristic circle."

It is therefore, evident that if vector representation is to be explained by means of polar coördinates, two distinct steps are necessary. 1st. The representation of the alternating value by a circle. 2d. The representation of the circle by its diameter. In the second step there remains the difficulty that the diameter does not completely represent the circle, and therefore only gives the maximum value and phase relation of the alternating sine wave.

With the above mentioned facts in mind, the following consideration will be clear.

1. That an alternating sine wave can be completely represented by a vector in a plane, is an established fact.

2. The clock and the polar coördinate methods are simply different means of explaining that fact.

3. To explain the fact by the polar coördinate method, requires two distinct steps, 1—that an alternating quantity can be represented by a circle, and 2—that the circle can be represented by its diameter.

4. The diameter of the circles does not completely represent the circle, and on that account only gives the maximum value and phase angle of the wave.

5. The diameter of the circle cannot be considered as a vector in the ordinary sense, for it cannot be moved to any parallel position without disturbing values of the intercepts.

6. It seems therefore, that it is impossible to fully demonstrate

the fact that an alternating sine wave can be completely represented by a vector by using the ideas of polar coördinates alone.

7. The ideas involved in polar coördinates cannot therefore, be logically offered as an argument for the employment of a particular convention in vector diagrams.

As given by Dr. A. E. Kennelly in his recent article on Vector Power (A. I .E. E. PROCEEDINGS, July, 1910), the clock diagram is used to explain vector representation, on the one hand by assuming a rotating vector and a fixed axis of projection; on the other hand by assuming a fixed vector and a rotating axis of projection. The direction of rotation in either case may be clockwise or counter clockwise. In this connection the following is suggested.

1. That on account of the universal use of counter clockwise rotation by mathematicians for positive rotation, it would seem preferable to use the same convention for vectors unless there is good reason to employ the opposite convention.

2. That since it is almost the universal practice, on account of greater simplicity, to consider an axis of reference as stationary, it therefore seems preferable in vector representations to refer to a stationary axis unless there is some good reason for employing the opposite convention.

O. J. Ferguson (by letter): In a discussion of the different systems of representing periodic functions, it may prove of value to outline some of the pros and cons and comment upon them briefly. In the following summary, points favorable to the use of the system are listed in the positive column. Unfavorable points are listed in the negative column. Not much can be determined by the comparison of the number of points, favorable or unfavorable, as some of those mentioned should be given much more weight than others. In the long run, however, systems should be compared by their relative total weights. No attempt has been made to attach such weights at this time as each person using any of the methods must determine that matter for himself.

Positive	Negative
Rectangular Coördinates.	
1. Concept of continuance of time	1. Impossibility of graphical methods of calculation.
2. Transient phenomena.	2. Inconvenient methods for combining waves analytically.
3. Non-sinusoidal waves.	
4. Direct evaluation.	
5. Visual comparison of successive instantaneous values.	
6. Summation of waves at any instant.	
7. Recognition of higher harmonics.	
8. Based upon a coördinate system.	

POSITIVE	NEGATIVE
Polar Coördinates.	
1. Based upon a coördinate system.	1. As vectors, the summation of instantaneous values is not direct.
2. Complete periodic cycle may be shown.	2. Visual comparison of successive instantaneous values is difficult.
3. Periodicity of cycle.	
4. Permanency of cycle.	
5. Direct evaluation when complete curve is used.	
6. Transient terms.	
7. Summation of waves at any instant, when complete curve are used.	
8. Derivation of effective value, etc.	
9. Use of vectors.	
10. Equivalent sine wave.	
11. Graphical calculations and imaginaries may be used.	
Crank Diagram.	
1. Periodicity of cycle.	1. A mechanical device for representing harmonic motion.
2. Graphical calculations and complex imaginaries may be used.	2. Complete cycle not shown.
3. Easy visual comparison of successive instantaneous values by projection.	3. Dual line position.
4. Summation of waves at any instant by projection.	4. Evaluation of instantaneous values by indirect methods, as projection.
	5. Suitable for sine waves only.

Rectangular Coördinates

POSITIVE

1. The x-axis extends to infinity and thus forcibly draws the attention to the continuance of time.

2. With the passage of time emphasized as above, transient phenomena are well shown.

3. Periodic deviations from sine waves are likewise easily recognizable.

4. Inasmuch as the curve is fully drawn, it is a simple matter to evaluate the function at any instant.

5. Ordinates, being parallel lines, are easily compared for their relative magnitudes.

6. In adding waves, their ordinates combine directly.

7. Many of the higher harmonics are easily recognized and they all have simple analytical expressions.

8. The whole conception is based upon a regular system of coördinate geometry.

NEGATIVE

1. It is very convenient to be able to represent the given function by some one thing (as a vector, in other systems) and use this thing for graphical calculations. This system does not admit such simplification.

2. The addition of waves analytically is not a simple process. That is, if

$$\sin \overline{\phi+30^\circ}+\sin \overline{\phi-15^\circ}=A \sin \overline{\phi+\alpha},$$

the evaluation of A and α is not as simple as the graphical solution nor does it appeal as quickly to the eye as does the latter.

Polar Coördinates

POSITIVE

1. The conception is based upon a regular system of coordinate geometry.
2. With periodic functions, the complete wave may be shown, whether it is regular or irregular in shape.
3. Angles above 360 degrees indicate a recurrence of the cycle, or periodicity of the function.

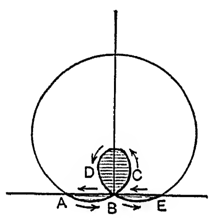


FIG. 1.—*A B C D B E B A*.—Current cycle in the center coil of the phase of an n-ring converter.

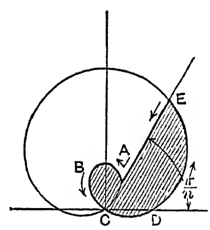


FIG. 2.—*A B C D E A*.—Current cycle in the end coil of the phase of an n-ring converter.

In each figure, the curved portion is taken at one sweep and the rectilinear portion occurs at the commutation point, or as the coil passes a brush. The complete curve, the limacon, is represented by the equation

$$I=I_1 \sin \theta \pm \tfrac{1}{2} I_0$$

where I_1 is maximum alternating current component and I_0 is direct current current

4. The presence of a single closed curve indicates the repetition of the cycle, or the permanency of the function.
5. The instantaneous value is directly obtainable for any time, along the radius vector corresponding to that time.
6. Transient phenomena shown thus give a direct comparison of successive cycles, indicating the waning of the transient term and the departure from the permanent cycle.
7. The summation of any number of waves is accomplished by the addition of their vectors.
8. The effective value of the function is readily obtained by the planimeter, which is of value in various calculations. For example, if a railway motor is rated in terms of its continuous current carrying capacity at the given voltage, plotting the variable current cycle by polar coördinates is a direct means of establishing a rating for the given motor or of choosing a motor to fit the given conditions.

Another instance may be taken from the field of synchronous converter phenomena. The accompanying figures show current cycles for the end coil and for the center coil of the phase of a converter armature winding. The enclosed areas vary as the square of the radius vector, that is, as i^2. The relative areas represent, therefore, relative heatings. Variation in the number of rings, change of power factor, choosing other coils of the armature, etc., may all be illustrated by their respective effects upon the polar diagram.

9. Sinusoidal functions may be represented by vectors, retaining the fundamental idea of the polar diagram. There is no change of view point.

10. A definite meaning can be given to the term "equivalent sine wave" in terms of equivalent areas.

11. The system lends itself readily to graphical calculations and to the use of the complex imaginary expression.

NEGATIVE

1. When the function is represented by a vector, a further development of the diagram is necessary in order to obtain instantaneous values or to combine instantaneous values. That is, to know the instantaneous value of a certain vector quantity, either (*a*) it must be projected upon the line whose displacement indicates the time or epoch, or, as is more usually done (*b*) the complete curve must be conceived as cutting off the infinite extension of this same line and limiting its length. The limited length is the value sought.

2. In comparing successive instantaneous values of the function, it is more difficult to estimate their relative values when the two (or more) lines compared are divergent. Parallel lines are much more easily contrasted.

Crank Diagram

POSITIVE

1. Successive revolutions of the crank indicate a recurrence of the cycle or a periodicity of the function.

2. Calculations may be made either graphically or by the use of complex imaginary quantities.

3. Successive instantaneous values may be compared by projection upon the 90 degree line or by the relative heights of the vector arrow-heads above the initial line. In one case, the lengths are measured along the same line, while, in the other case, they are measured along parallel lines and, in either condition, inequality is easily recognized.

4. After projection upon the 90 degree line, instantaneous values may be added, directly. (This seems slightly simpler than having to project upon the general vector or than drawing the full curve.)

NEGATIVE

1. The conception used is that of a crank revolving mechanically, one component of its extension illustrating harmonic motion. As such, it is effective but its range beyond a few of the general applications is limited. It is proper to note that the limited range does cover the most common and, probably, most useful applications of the vector principle.

2. The complete cycle cannot be represented by any curve upon the diagram, as all instantaneous values are measured along the same line—the 90 degree line.

3. The complete concept of the function, as regards phase and magnitude, requires *two* elements for its expression. That is, a *crank position* represents phase condition, while the magnitude of the variable is indicated by a *length along a different line*. This is in contradistinction to a vector which represents phase condition (epoch) by position and also shows magnitude by its own length.

4. As a result of the inability to show the complete curve, instantaneous values can be obtained only by projection.

5. It cannot properly be called a system for representing *periodic* functions but must be limited to *sinusoidal* functions. Transient terms, higher harmonics, converter current cycles, etc., can not be exhibited.

The point at issue in the discussion before the Institute is as to the relative values of the *crank diagram* and the *vectorial side of the polar diagram*. Inasmuch as the polar diagram is broad enough to cover the whole field *including* vector representation, and it must be used for certain purposes quite beyond the range of the crank diagram, is it not advisable to meet on the common ground of the most usable system? In some problems, polar coördinates have decided advantages over rectangular coördinates. Shall we depend wholly upon the latter and the crank diagram, to the exclusion of the polar system? Or, are we best served by keeping all three schemes in mind in a more or less muddled condition? Undoubtedly, usage is what will settle the question and, probably, the engineering public will standardize what they wish.

C. A. Adams (by letter): Arguments on both sides of this question have been in print for some time, and it seems undesirable to take the subject up at any length at this late hour. I should like, however, to present one argument, which, as far as I know, has not been presented before.

It is claimed for the polar coördinate method of representation, that the root-mean-square value may be readily determined by planimetering the polar curve of the alternating quantity in question; but this is only occasionally desirable, and then only in the case of a complex wave, in which case the polar curve is not a circle and therefore has no diameter by means of which it can be represented. In fact the representation of alternating currents or e.m.fs. by vectors, ceases to be in any sense exact

when the quantities in question deviate much from the simple sinusoidal type; but when such deviation exists, we can handle the problem satisfactorily only by the aid of harmonic analysis, practically all of the methods of which require the wave to be plotted in *rectangular* coördinates.

But after all the question at issue must finally be settled by usage rather than by arguments based on any fundamental merits of the case; it is a conventional part of our alternating current language upon which we must agree, if we are to avoid an enormous waste of energy on the part of all students of this subject. I for one will gladly abide by the general consensus of opinion if it can be obtained, even though it involves a reversal of my habitual notation.

We talk much about the efficiency of apparatus, and make much of a saving of one per cent but we keep on using mixed systems of notation and of units, which involve a much larger reduction in the efficiency of the engineer himself.

A paper presented at the 258th meeting of the American Institute of Electrical Engineers, Boston, February 17, 1911.

ECONOMIC LIMITATIONS TO AGGREGATION OF POWER SYSTEMS

BY ROBERT A. PHILIP

Limitations on the distance to which power can be transmitted electrically have been investigated from time to time. In this paper it is the purpose to point out that the limiting distance of transmission is not the limit of economical interconnection and that there is probably no such limit. It is also the purpose to outline certain principles of electric transmission which indicate the line along which unlimited extension of electric networks may proceed.

Electric power promises to become the universal power of the future. It is not a substitute for steam power or water power; it competes with no prime mover. Electric power is essentially a secondary power. Prime movers produce useful but crude mechanical power from the rough, irregular forces of nature. Mechanical power, transformed and refined in the electric generator, becomes electric power, the highest known form. The highest form because it can be changed to other forms, heat, light, motive power, chemical action with unparalleled directness and simplicity. It is the uniform method of applying any kind of power from any source to any work. To other powers it stands as a common medium of exchange. Prime power is like property, electric power like money.

The electric motor consumes electric power produced by an electric generator driven by a prime mover. When an electric motor is substituted for a steam engine the load is merely transferred from one prime mover to another. There is a loss of power in the electric generator, a loss in the electric transmission line and a loss in the electric motor. In spite of these losses

electric transmission and distribution of power is commercially successful because of economy, flexibility and cleanliness.

The motor is economical merely because the prime mover on which it ultimately depends is still more economical; that is, electric power is an advantageous means of producing competition between different prime movers and thereby displacing those that are wasteful. Every circumstance unfavorable for economical power generation can be found in varying degrees among isolated plants while central electric generating plants may take advantage of every practicable economy. Certain highly important differences favorable to centralized prime movers are greater size, greater diversity factor, greater load factor, convenient location for fuel and water and cheap land. Of these some are automatically cumulative. As the plant grows its economy increases and as the economy increases it surpasses that of more and larger isolated plants, displaces them and thereby grows some more. Furthermore, electric power is not limited to bringing a large prime mover into competition with a small prime mover of the same kind; it goes farther, taking for its source any other kind of prime mover which may be more economical. The economy of electric power is essentially progressive and is only limited by that of the best prime mover of any size, any kind, anywhere.

Power is used to produce results. The requirements for economical production and economical application of power are antagonistic. Concentration and continuity are essentials for favorable production, while subdivision and controllability best adapt it to its uses. Electric power reconciles these diverse requirements. While concentrated at the continuously running generator, it is subdivided at the intermittently running motors.

Essentially a secondary power, it consumes no raw material and emits no waste material. No water or fuel goes in, no ashes, water or gases come out. Increased human activity and efficiency require and depend on increased power, per capita, per square mile, per cubic yard. Contamination of the air by prime movers sets an artificial limitation to beneficial concentration. Electric power removes the limitations and opens up new possibilities. The modern city subway can be operated by electricity and by that alone.

The principle underlying the success of electric power is that of uniformity. Incidentally, to be uniform, the method must be indirect. The same principle underlies the use of money.

Property may be exchanged directly by barter, but the uniform method of indirect exchange by purchase and sale is superior. In each case the intermediate medium of exchange gives the flexibility necessary for equalizing production and consumption on a large scale. The public service corporations which distribute power have a function analogous to a banking system. They constitute clearing houses for balancing the individual increases and decreases of power requirements of a community as a whole and provide a centralized reserve for meeting promptly any total net increase.

The power plant which does not use electric power stands alone. In the continual readjustment of industry, there are shifting deficiencies and surpluses of power which cannot be economically met by increasing, decreasing and moving local prime mover power plants. In the aggregate, the disproportion of the isolated prime movers to their loads must be enormous. This leads to the conclusion that there is a great collateral advantage in using electric power, wherever practicable as an intermediate step between the prime mover and the work, thereby providing the necessary means of immediately and without further expense participating in the advantages of uniting resources with the rest of the community whenever emergency, convenience or economy require it.

The success of electric power distribution and transmission has been due largely to two specific applications of the underlying principle of uniformity. First, that it is cheaper to generate power by steam in one large plant than in numerous little plants. Second, that steam power may be economically superseded by otherwise impracticable water powers. These two applications have built up two classes of transmission systems, those from central steam plants originating at the large centers of population and radiating into the country where they supply current for railways, light and power in outlying towns and villages; those from water powers starting from the mountains and converging toward the cities. These applications alone, though stimulated by increased consumption and higher price of fuel, may extend the economical radius of transmission, but not indefinitely.

On the other hand, if there is no increase in the economical radius, nevertheless, the continued development which may be reasonably expected along present lines will in time cover the country with high-tension distribution and transmission lines.

These lines will form short contiguous but independent transmission systems each one having a specific function of distribution or transmission which pays for the interest on the investment the repairs and maintenance and the cost of power used up in core loss and other friction or leakage necessary for keeping the system alive. While each line is useful and necessary, every line is subject to periods when it is idle. In other words, its load factor is low. During off peak hours, power can be transmitted subject to no charge for interest, repairs or maintenance and free of deduction for the constant losses of the system. Devoid of these encumbrances, the usual limitations to the distance to which power may be transmitted do not hold.

This opens the way to a broader application of the principle of uniformity. The differences in economy between large and small steam plants and between steam and water power plants are not the ultimate limitation to transmission. Were the limitations reached in these two directions there remains a vast field of economy in applying the principle in other directions.

Diversity factor alone contains almost inconceivable possibilities. Wherever there is intermittent work diversity factor may be expected. In so far as it is unnecessary to do two different things simultaneously it should be unnecessary to duplicate the power supply. Since the point of application of electric power may be instantly transferred from place to place, only a half (or other fraction, as the case may be) of the prime power is required in a central plant which would be needed in two or more separate local plants. This fraction is the diversity factor. It has already done much to enhance the advantage of the large plant over the small one but the large plants in turn are governed by local conditions and, like the isolated plants they supplant, they have important diversity factors among their loads. Thus the conditions determining the hour of peak vary considerably in different cities, with the industries and customs of the inhabitants, with local weather conditions, with the altitude, latitude and longitude; the artificial convention of standard time makes an hour's difference in time of starting work in nearby cities and over greater distances the natural difference in time makes greater differences.

Water powers have a peculiar species of diversity factor of production due to non-coincidence of deficiencies. While there are dry years in which all water powers may suffer deficiency, the idea of coincident deficiencies is largely due to insufficient

and inaccurate records. From the nature of the case the rains, snow fall, freezing and thawing must vary widely according to the location and exposure of the watersheds. There will be some diversity between the flow of any two streams though they be adjoining, a greater diversity between those on opposite sides of a divide, and more between those on different mountain groups. A large river which runs dry for short periods for lack of storage and a large reservoir on a small stream are each defective for power supply, but together they may be mutually supplementary. By combination the bulk of the power may be derived from rivers on one watershed, the reserve storage from those on another.

Economy of reserve is another application. The large plant gives centralized reserve, the large system gives a diversity factor among accidents and an interchange of reserve.

More remotely the general extension of transmission may open up possibilities of developing the intermittent powers of nature which, variable and unreliable in any one locality, may, taken over a large area, or in connection with each other or with existing developments, be found to be uniform and reliable. Thus the tides occur at different hours at different points. Variable powers such as the wind have appeared impracticable largely because they have never been studied adequately, and if developed locally, require a prohibitive expense for regulating, equalizing and storage. Comprehensively developed as an auxiliary to an established system which could use the power as available, the cost of power from these sources would be far less than has been heretofore supposed.

Transmission lines are the highways of power. Having made power portable and universally applicable by reducing it to the electric form, it is inconceivable that the highways over which it travels will not be vastly more useful if interconnected.

More definitely, there is the present problem of existing transmission systems growing beyond the bounds for which they have been designed by the annexation of adjoining independent systems as one by one the collateral advantages pass into the domain of accepted fact.

To design a transmission line to transmit power from a water power plant to a city is a definite problem. To interconnect two such lines to accomplish some auxiliary purpose not in the original design is quite a different problem. The interconnection of two transmission systems is like combining two rail-

roads, first, there must be a physical connection, then unified operation. As the gauges of the railroads must be reconciled, so the frequencies, phases and voltages must be adapted by reducing to a common standard or the power must be converted at the junction points. Then the flow of power in the network must be controlled so that, within the limitations of the wires provided, power may be transferred at will from points of surplus to those of deficiency. This problem of interconnection differs from that of transmission in introducing as an element the idea of reversible transmission, that is, either end of the line may be generating or receiving end.

The interconnection of two systems forecasts future connection with a third and fourth. Such extension carried on indefinitely, leads to the conception of a single vast system which may be built up in the future. Electric power is successful because it is the one uniform method of equalizing supply and demand. Every extension and interconnection broadens the field in which it can act and should increase its success. Continued, indefinite extension is desirable and inevitable if possible.

As electric power is like a common denominator to which all other power is reducible, so alternating current is the common form to which electric power itself must be reduced to become universally available. Direct current is useful and necessary but its function, for the present at least, is that of a form auxiliary to or derived from alternating current and limited in the distance which it can travel to a single locality. Alternating current combines a suitability to the high pressure necessary for transmitting power in bulk long distances with a simplicity of division and subdivision both of power and pressure which is necessary for the ultimate distribution. Furthermore, the alternating current system has unique qualities which especially suit it for reversible operation, and thereby adapt it for indefinite extension.

Electric currents are commonly regarded as flowing from points of higher potential to those of lower potential. With direct currents the potential of the generating end of the line must be higher than that of the receiving end directly in proportion to the power delivered in order to overcome the line resistance. With alternating currents delivering the same power over the same line at the same voltage and at unity power factor, the potential of the generating end must be still higher as the reactance as well as the resistance of the line must be overcome

even if the power is delivered at unity power factor, which is usually regarded as the most favorable case for alternating transmission. If the power is delivered to an inductive load the power factor will be lower than unity and the potential of the generating end must be higher yet in order to force the magnetizing current over the line in addition to the working current.

To provide for the variation of drop of potential in a transmission line at varying loads numerous devices are used. The generator voltage may be varied through adjustment of the field rheostat or by compounding; the ratio of step-up and step-down transformers may be made different so that the generator voltage will be the same as the receiver voltage at full load instead of at no-load, as would be the case if the transformers had the same ratio; or separate boosting transformers may be used to the same end; a regulating dial connected to taps to the transformer windings may be used to vary their ratio, or a regulator consisting of a separate transformer of variable ratio may be used for the same purpose.

While in ordinary alternating-current transmission supplying only lights and induction motors the potential at the generating end is necessarily higher than at the receiving end, in a transmission line supplying a synchronous motor taking a leading current the condition may be reversed and the potential may be higher at the receiving end than at the generating end so that the current flows from a point of lower to one of higher potential.

While leading currents may cause the potential at the receiving end to be higher than at the generating end they do not do so necessarily. With a large amount of leading current the potential may be higher at the receiving end but with a small amount it may be lower and with an intermediate amount it may be the same at the two ends and may be maintained the same even if the load varies by a corresponding variation in the amount of leading current.

Power may therefore be transmitted over a line by alternating currents without change of potential and a system may be built up by adding other lines until a network is formed uniting many power houses and many substations. In such a system the potential may be the same at the bus bars of every power house and every substation and yet power may be transferred at will through the network in any direction. Since the potential at the edges of such a network is the same as at the center it is evident that the system is capable of indefinitely

great extension. While the power is transmitted without loss of potential there is a loss of energy equal to the square of the current multiplied by the resistance as usual. The possibility of extension is not for the transmission of power in bulk for indefinitely great distances but rather for the extension of a network containing points of generation at intervals, the load being equalized on the points of generation by means of the network which permits of power being transmitted to or from any point in any direction for distances as great as considerations of emergency or economy may indicate from time to time.

In view of the customary drop of potential from the generating to the receiving end of the line, transmission without this drop may at first seem to be an abnormal and unstable condition but this is not the case.

Suppose two identical machines connected by a line, one run as an alternator and the other as a synchronous motor. If the resistances and reactances of the armatures are so small as to be negligible and if the strengths of the fields are so great compared to that of the armatures that the effect of armature reaction is negligible then this combination will automatically transmit the power with constant potential at each end of the line independent of load and of line impedance. If the armatures of the machines have appreciable resistance or reactance there will be a drop of potential from no-load to full load but it should be noted that the drop results from the resistances and reactances in the machines, not those in the line. It is therefore only necessary to improve the regulation of the machines themselves to attain a natural constant potential transmission system.

To operate a synchronous motor on the constant-potential system we should therefore adjust its field, not according to a power factor meter but according to a voltmeter on the line as it is normal line voltage, not unity power factor on the motor, which is desirable. The condition, previously assumed, that the synchronous motor is a machine which is a duplicate of the generator is not essential, also any other kind of load may at the same time be supplied by the same line. Where both synchronous and induction motors are operated from the same line the voltmeter method of adjustment has the advantage of simplicity in that the proper adjustment of the field of the synchronous motor for overcoming the lagging currents of the induction motors is obtained thereby although the currents taken by the induction motors are unknown to the one making

the field adjustment. Where synchronous motors are used on lighting systems the advantage of operating them on the constant potential system is obvious for if correctly operated in this manner the regulation of the system, which is of prime importance, becomes perfect.

Taking again the case of the two-machine transmission just considered. Suppose a mark made on some point of the rotor of the generator and a similar mark at the corresponding point of the rotor of the motor. At no-load the marks will reach the top of the circles in which they revolve at the same time indicating that the voltage of the motor is in phase with that of the generator; as the load comes on the mark on the motor will fall behind that on the generator, reaching the top position a little later, indicating that the voltage of the motor is falling behind that of the generator. This illustrates the principle that in constant-potential transmission current flows and power is transmitted from points of advanced to those of retarded phase. In other words the potential of the receiving end must drop behind that of the generating end in phase instead of below it in magnitude.

In a direct-current transmission with constant generator potential the amount of power transmitted increases with increased drop of potential up to a certain maximum and then decreases again, so with constant potential alternating transmission the amount of power increases with increased retardation of potential phase up to a maximum and then decreases again. In each of these cases the range from no-load to the maximum load is the range of stable operation, beyond the maximum is a range of unstable operation. In each case too, the maximum power which may be transmitted depends on the constants of thė line. The greater the resistance the less power that may be transmitted by either direct or alternating currents. The analogous assumption that the greater the line reactance the less the power that may be transmitted by alternating currents is incorrect. With no line reactance no power could be transmitted at constant potential, but as all lines have some reactance this case would never actually occur. Up to a certain limit the greater the line reactance the greater the maximum amount of power which may be transmitted. For every transmission line there is therefore a range of stable operation for constant potential transmission.

The utility of a system of transmission depends partly on the

ease with which its operation can be foretold by calculation. On this basis the constant potential system is at a great advantage for its characteristics can be shown in a simple diagram constructed from constants which are readily calculated and have an easily understood physical meaning.

Geometrically the flow of power is represented by straight lines and circles, algebraically by quadratic equations both expressed in terms of the amount of power the line takes when short circuited.

The calculations and the conclusions from them are given in more detail in a supplement to this paper. The results show that:

The constant potential alternating system is on a par with direct current as to the amount of power and as to the efficiency of transmission over a line of given resistance and voltage.

A comparatively high line reactance is a favorable feature both as regards amount and efficiency of power transmission and therefore a frequency of 60 cycles per second may be better than one of 25 cycles for power transmission.

Reactance makes a line opaque to short circuits but wattless power introduced at the receiving end makes it transparent to the flow of useful power, therefore the power at short circuit may be less than at full load.

A short circuit may be a local matter not interrupting the service of the system as a whole, not affecting the voltage except for a limited radius, and not draining any extraordinary amount of power from the system.

Switches of limited capacity may be safely used on systems of unlimited power.

Blocks of power too great to be safely controlled may be subdivided by artificial lines instead of being entirely separated.

There are no limitations to amount of phase difference, therefore none to unlimited extension at constant potential, but in distant parts of a large system the difference may be so great that one machine may be one or more complete cycles (or even revolutions) behind another.

In interconnecting different branches of a large system the actual as well as the apparent phase difference must be considered, therefore the readings of any ordinary synchronizing device may fail to indicate the true phase relation.

Constant potential transmission requires controllable leading currents, synchronous motors are the practical source of such

currents, therefore the first step in establishing such a system is to have as large a part of the receiving equipment as possible composed of synchronous motors, to have these motors designed for carrying full load with leading currents of say 80 per cent power factor, and to have their voltage controlled by non-compounded voltage regulators.

Rotary converters are synchronous motors, but as ordinarily constructed are poorly adapted for operation with leading currents.

The electrostatic capacity of transmission lines furnishes leading currents which are not directly controllable and are therefore not the equivalent of those from synchronous motors.

Synchronous motors can take lagging as well as leading currents, but the lagging currents taken differ from those of induction motors in being controllable.

The leading currents of line capacity and the lagging currents of induction motors subtract and add respectively certain amounts to the available leading currents to be furnished by the synchronous motors, that is, they do not affect the range of control required but rather shift the mean position of this range toward lagging or leading respectively.

To summarize the principles here outlined. First is that of the solidarity of the power market as a whole, next is that of the place of electric power in this market which, not itself a prime power yet is the common medium of exchange for all prime power. From this follows naturally the indefinite extension and interconnection of transmission lines, the highways of power. Underlying all these is the requirement that electric power though poured in unlimited amounts into a system of indefinitely great extent must be as mobile as the trains on the country's railroad network, must be universally uniform in quality, must never be totally interrupted and though in amount unlimitedly great must not be uncontrollable. To meet these requirements electric power must take the alternating-current form and should be transmitted on the constant-potential system. Finally, this system is one using high line reactance made transparent by leading wattless currents and transmitting power by displacing the phase of the voltage instead of varying its amount.

Supplement

Below are developed certain formulæ for the transmission of power by alternating currents at constant potential.

Before deriving the formulæ for the construction of the dia-

gram the meaning of the constants in terms of which the results will be obtained may be explained and their method of calculation shown.

We are now considering a certain line (single-phase) which is to be operated at a constant potential E. The resistance of the line is R, its reactance X and its impedance Z; these are calculated from tables in the usual way by multiplying the tabulated values per unit of length by the length of the line.

Consider now that one end of the line is maintained at potential E and the other end short circuited. A short circuit current I will flow. By the analogy to Ohm's law which holds for alternating currents, the current I is equal to the potential divided by the impedance or E/Z. To maintain this short circuit current requires power equal to $I\,E$ or its equivalent $I^2\,Z$ apparent watts. The apparent watts $I^2\,Z$ for which we may write W_3 are composed of two components, the "true" watts $I^2\,R$ and the "wattless" watts $I^2\,X$ for which we may write W_1 and W_2 respectively.

Consider next that the potential at one end of the line is maintained at the same potential E but with direct instead of alternating current, and the other end is short circuited as before. A short circuit current I' will flow. By Ohm's law the current I' is equal to the potential divided by the resistance or E/R. To maintain this short circuit current requires power equal to $I'\,E$ or $I'^2\,R$ watts. For this power absorbed by the short circuit current we may write W.

The four constants W_1, W_2, W_3, and W are all that are required for the construction of the constant potential transmission diagram. They are interpreted physically as power absorbed by the line at short circuit. The first three are respectively the "true", "wattless" and "apparent" power absorbed at short circuit with alternating current and the last one is the power absorbed at short circuit with direct current. Of the four constants there are really only two independent, the other two being used for simplicity and symmetry of expression and for aid in the physical interpretation of the resulting equation. Thus any two may be eliminated by the use of the relations shown algebraically in equations (**16**) and (**26**) given hereafter, or shown geometrically by the two equivalent constructions illustrated in Fig. 2 and Fig. 3, respectively.

The derivation of the formula for the constant potential transmission diagram is from the auxiliary voltage diagram shown in Fig. 1 as follows:

Fig. 1 represents the voltage relation in a line transmitting any amount of power (say w_1) at constant potential. In addition to the true power w_1 delivered there will also be of course a wattless component w_2, the resultant of the two components being the apparent power w_3 delivered.

The voltages at the generating and receiving end are each equal to E. That at the receiving end is behind that of the generating end by the angle θ. The current i is necessarily leading at the receiving end and is ahead of the potential at that end by the angle α. The cosine of α is therefore the power-factor of the receiving end and the sine of α is the inductance factor. The potential at the receiving end being out of phase with that of the generating end there is a difference of potential e between the two ends of the transmission line in spite of the fact that the potentials at the two ends are numerically equal. Since the line is necessarily inductive the current i must lag behind the potential e by an angle ϕ. The cosine of ϕ is therefore the power factor of the line itself and the sine of ϕ its inductance factor. The diagram is now completed by drawing lines showing the resolution of the received voltage E and line voltage e into components in phase with and in quadrature with the current and by drawing a line bisecting the angle θ which line consequently becomes a perpendicular to e.

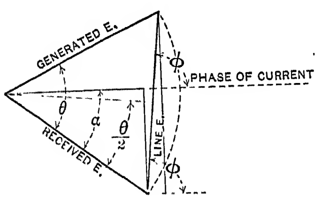


FIG. 1.—Voltage diagram

From the diagram we find by elementary geometry:

$$\alpha - \frac{\theta}{2} = \frac{\pi}{2} - \phi \tag{1}$$

By trigonometric reduction of (1):

$$\sin \frac{\theta}{2} = -\cos (\alpha + \phi) \tag{2}$$

$$\sin \frac{\theta}{2} = \sin \alpha \sin \phi - \cos \alpha \cos \phi \tag{3}$$

From the diagram again:

$$\sin\frac{\theta}{2} = \frac{e}{2\,E} \tag{4}$$

From the law of the alternating circuit applied to normal and short circuit conditions respectively:

$$e = i\,Z \tag{5}$$

$$E = I\,Z \tag{6}$$

Changing e/E by substituting values given in (5) and (6), transforming algebraically and using definitions of w_3 and W_3 as apparent watts:

$$\frac{e}{E} = \frac{i\,Z}{I\,Z} = \frac{i}{I} = \frac{i\,E}{I\,E} = \frac{w_3}{W_3} \tag{7}$$

Substituting (7) in (4):

$$\sin\frac{\theta}{2} = \frac{w_3}{2\,W_3} \tag{8}$$

From the definitions of power factor and inductance factor:

$$\cos\alpha = \frac{w_1}{w_3} \tag{9}$$

$$\sin\alpha = \frac{w_2}{w_3} \tag{10}$$

From the fact that the power factor and inductance factor of the line are the same at all loads including short circuit:

$$\cos\phi = \frac{W_1}{W_3} \tag{11}$$

$$\sin\phi = \frac{W_2}{W_3} \tag{12}$$

Substituting (8), (9), (10), (11) and (12) in (3):

$$\frac{w_3}{2\ W_3} = \frac{w_2\ W_2}{w_3\ W_3} - \frac{w_1\ W_1}{w_3\ W_3} \tag{13}$$

By algebraic reduction of (13) :

$$w_3^2 = 2\ (w_2\ W_2 - w_1\ W_1) \tag{14}$$

The relation between apparent power and its components is:

$$w_3^2 = w_1^2 + w_2^2 \tag{15}$$

$$W_3^2 = W_1^2 + W_2^2 \tag{16}$$

Substituting (15) in (14):

$$w_1^2 + w_2^2 = 2\ (w_2\ W_2 - w_1\ W_1) \tag{17}$$

By algebraic transformation of (17):

$$(w_1 + W_1)^2 + (w_2 - W_2)^2 = W_3^2 \tag{18}$$

(18) is the formula desired.

Interpreting (18) as an equation of a curve with w_1 and w_2 as variables we see that it represents a circle with its center at $-W_1$, W_2 and of radius W_3, therefore passing through the origin.

A diagram in which the power is represented by the position of a point, the rectangular coördinates of which are the true and wattless components of the delivered power may be called a power diagram. In such a diagram the polar coördinates of the same point represent by the radius the apparent power delivered and by the angle the phase difference between delivered current and delivered potential. Since phase difference between current and potential is determined by power factor it may be more conveniently designated by power factor as the angular coördinate.

We may now take a concrete example and construct the diagram. Take say a transmission line 11 miles (17.7 km.) long composed of two No. 0000 wires spaced 18 in. (45.7 cm.) on centers and assume that power is to be transmitted at 60 cycles per second at 11,000 volts.

From a table we find for No. 0000, 18-in. (45.7 cm.) spacing, 60 cycles:

Resistance 0.049 ohms per 1000 ft. (304.8 m.) of wire.
Reactance 0.106 " " " " " "
Impedance 0.117 " " " " " "

If impedance is not given it may be calculated from the resistance and reactance thus: $\sqrt{(0.049^2+0.106^2)} = 0.117$.

From these we compute for the line:

Resistance $0.049\times2\times5.28\times11 = 5.69$ ohms
Reactance $0.106\times2\times5.28\times11 = 12.3$ "
Impedance $0.117\times2\times5.28\times11 = 13.6$ "

The short circuit current would be
$11000/13.6 = 809$ amperes.

The power required to maintain the short circuit would be:

True power, $809\times809\times5.69/1000=3720$ kilovolt-amp.(kw.)
Wattless power, $809\times809\times12.3/1000=8060$ "
Apparent power, $809\times809\times13.6/1000=8900$ "

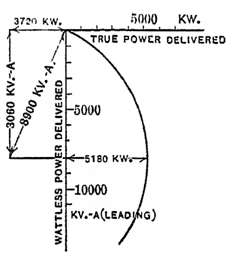


FIG. 2.—First construction of power diagram

The latter figure may also be computed more easily thus:
$809 \times 11000/1000 = 8900$ kilovolt-amperes.

The center of the circle is therefore at point $-$ 3720, 8060, and the radius is 8900, and we construct the diagram Fig. 2 accordingly.

We may determine the maximum amount of power which may be transmitted over the line at constant potential by inspection of the diagram as 5180 kw. A general formula for the maximum power may be derived from the diagram or from equation (**18**) rewritten as follows:

$$(w_1+W_1)^2=W_3^2-(w_2-W_2)^2 \tag{19}$$

Since W_1, W_2 and W_3 are constants $(w_1+W_1)^2$ and consequently w_1 will have a maximum value when $(w_2-W_2)^2$ is negative or a minimum. The square of (w_2-W_2) cannot be negative and its minimum value is zero, therefore the maximum value is given by

$$(w_1+W_1)^2=W_3^2 \tag{20}$$

or

$$w_1=W_3-W_1 \tag{21}$$

Stating this result in words: The maximum amount of power which may be transmitted over a line at constant potential and given frequency is equal to the difference between the apparent and the true power necessary to maintain the short-circuit current of the line at the same voltage and frequency.

The calculations made are all for single-phase circuits but they are equally applicable to three-phase, three-wire and two-phase, four-wire circuits of the same size wire and spacing by simply doubling the amounts of power in every case. This can also be done by giving the power diagram a double scale, making it applicable to single, two- or three-phase circuits.

We may next determine the influence which frequency has on the use of a line for constant potential transmission.

The resistance of the line may be taken as independent of frequency but the reactance and impedance will vary with the frequency and consequently the constants W_1, W_2 and W_3 will have different values for different frequencies.

The short-circuit condition for a direct-current line gives, from Ohm's law:

$$W = I'^2 R = \left(\frac{E}{R}\right)^2 R = \frac{E^2}{R} \tag{22}$$

Similar equations for an alternating-current line are:

$$W_3 = I^2 Z = \left(\frac{E}{Z}\right)^2 Z = \frac{E^2}{Z} \tag{23}$$

$$W_1 = I^2 R = \left(\frac{E}{Z}\right)^2 R \tag{24}$$

Squaring (**23**) gives

$$W_3^2 = \frac{E^4}{Z^2} = \left(\frac{E}{Z}\right)^2 . E^2 = \left(\frac{E}{Z}\right)^2 R . \frac{E^2}{R} \tag{25}$$

Substituting (**22**) and (**24**) in (**25**) gives:

$$W_3^2 = W_1 W \tag{26}$$

Substituting the value of W_3^2 in terms of its components:

$$W_1^2 + W_2^2 = W_1 W \tag{27}$$

By algebraic reduction of (27)

$$\left(W_1 - \frac{W}{2}\right)^2 + W_2^2 = \left(\frac{W}{2}\right)^2 \qquad (28)$$

The latter is the desired relation. We see from it that the centers of the various circles representing the operation of the line at different frequencies lie on another circle whose center is at the point $\frac{W}{2}$, 0 and of radius $\frac{W}{2}$.

As an example we may construct the diagram for the line previously considered at various frequencies.

As previously computed we have, resistance, 5.69 ohms; the short-circuit (direct) current is, therefore,

11000/5.69 = 1930 amperes.

Power required to maintain the short circuit is
$1930 \times 11000/1000$
$= 21300$ kw.

Taking half of this we have, 10650 kw.

The center of the new circle is therefore at the point − 10650, 0 and the radius is 10650 and the diagram is as shown in Fig. 4.

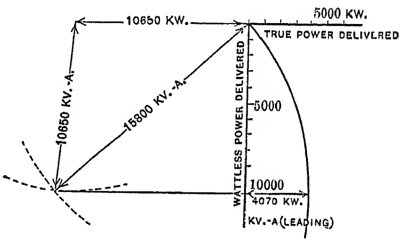


FIG. 3.—Second construction of power diagram

The construction of the diagram shows that instead of determining the location of the center of the circle representing the operation at a given frequency from the true and wattless components (W_1 and W_2) of the short-circuit power as previously done it may equally well be located from the (apparent) power necessary to maintain short circuit by alternating and direct current respectively (W_3 and W).

The use of this construction for determining the center of the circle when the transmission line already considered is operating at 25 cycles is shown in Fig. 3.

The complete calculation is as follows:

From the table we find for No. 0000, 18-in. (45.7 cm.) spacing, 25 cycles:

Resistance, 0.049 ohms per 1000 ft. (304.8 m.) of wire.
Impedance, 0.066 " " " " " "

For the line we compute
Resistance, $0.049\times2\times5.28\times11=5.69$ ohms.
Impedance, $0.066\times2\times5.28\times11=7.65$ "
The short circuit current is:
Direct current, $11000/5.69=1930$ amperes.
Alternating current, $11000/7.65=1440$ "
The power to maintain the short circuit is:
Direct current, $1930\times11000/1000=21300$ kw.
Alternating current, $1440\times11000/1000=15800$ kilovolt-amperes and $21300/2=10650$ kw.

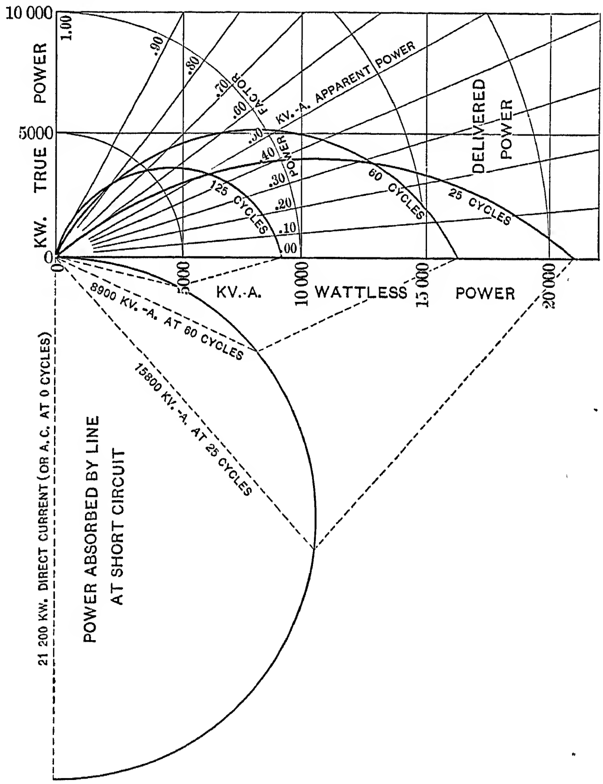


FIG. 4.—Power diagram

Adding now to Fig. 4 the circles for 60 and 25 cycles as computed above and also adding that for 125 cycles computed in a similar manner, we find that for the particular line considered, more power can be transmitted (at constant potential) at 60 cycles than at either 25 or 125 cycles, the respective maxima being:
25 cycles, 4070 kw.; 60 cycles, 5180 kw.; 125 cycles, 3660 kw.

The amount of power which can be transmitted over this line at 25 cycles could be increased by artificially increasing the reactance of the line by the use of reactance coils.

To determine what frequency permits of the greatest amount of power being transmitted over any line (without the use of reactance coils) we take the previously written equations (**21**) $w_1 = W_3 - W_1$, and (**26**) $W_3^2 = W_1 W$:
Substituting values of W_1 from (**26**) in (**21**) gives

$$w_1 = W_3 - \frac{W_3^2}{W} \tag{29}$$

Algebraic reduction of this gives

$$w_1 = \frac{1}{W}\left[\left(\frac{W}{2}\right)^2 - \left(\frac{W}{2} - W_3\right)^2\right] \tag{30}$$

The maximum value of w_1 would occur when the square of $\left(\frac{W}{2} - W_3\right)$ was negative, but as that is impossible it occurs when the square is 0; therefore when

$$W_3 = \frac{W}{2} \tag{31}$$

Substituting this value in (**26**)

$$W_1 = \frac{W}{4} \tag{32}$$

Substituting from (**31**) and (**32**) in (**21**)

$$w_1 = \frac{W}{4} \tag{33}$$

Dividing (**32**) by (**31**) gives

$$\frac{W_1}{W_3} = \frac{1}{2} \tag{34}$$

Equation (**34**) may be stated as follows: The greatest amount of power can be transmitted over a line (at constant potential) at that frequency which makes the power factor of the line itself 50 per cent.

Since the greatest amount of power that can be transmitted over a line by direct current is one fourth of that necessary to maintain short circuit by direct current, equation (**33**) may be interpreted as follows:

The greatest amount of power that can be transmitted over a line (at constant potential) at most favorable frequency is the same as the greatest amount that can be transmitted over the line by direct current with the same initial voltage.

The formulæ given refer to delivered power; a similar relation holds for generated power. Thus, if the true, wattless and apparent line losses are w_1', w_2' and w_3' and the corresponding components of the power generated are, w_1'', w_2'' and w_3''.

$$w_1 = w_1'' - w_1' \tag{35}$$

$$w_2 = w_2'' + w_2' \tag{36}$$

From the equality of potential and current at the generating and receiving ends of the line:

$$w_3 = w_3'' \tag{37}$$

From Fig. 1

$$w_3' = i\,E\,2 \sin\frac{\theta}{2} = w_3\,2 \sin\frac{\theta}{2} \tag{38}$$

From (**8**)

$$w_3' = \frac{w_3^2}{W_3}. \tag{39}$$

From this

$$\frac{w_3^2}{W_3^2} = \frac{w_3''^2}{W_3^2} = \frac{w_3'}{W_3} = \frac{w_2'}{W_2} = \frac{w_1'}{W_1} \tag{40}$$

These substituted in (**35**) and (**36**) give

$$w_1 = w_1'' - w_3''^2 \cdot \frac{W_1}{W_3^2}. \tag{41}$$

and

$$w_2 = w_2'' + w_3''^2 \cdot \frac{W_2}{W_3^2}. \tag{42}$$

Substituting these values in (**14**) gives

$$w_3''^2 = 2\left(w_2'' W_2 + w_3''^2 \frac{W_2^2}{W_3^2} - w_1'' W_1 + w_3''^2 \frac{W_1^2}{W_3^2} \right) \quad \textbf{(43)}$$

Reduction of this gives

$$w_3''^2 = 2\ (w_1''\ W_1 - w_2''\ W_2) \quad \textbf{(44)}$$

By algebraic transformation (**44**) may be rewritten

$$(w_1'' - W_1)^2 + (w_2'' + W_2)^2 = W_3^2 \quad \textbf{(45)}$$

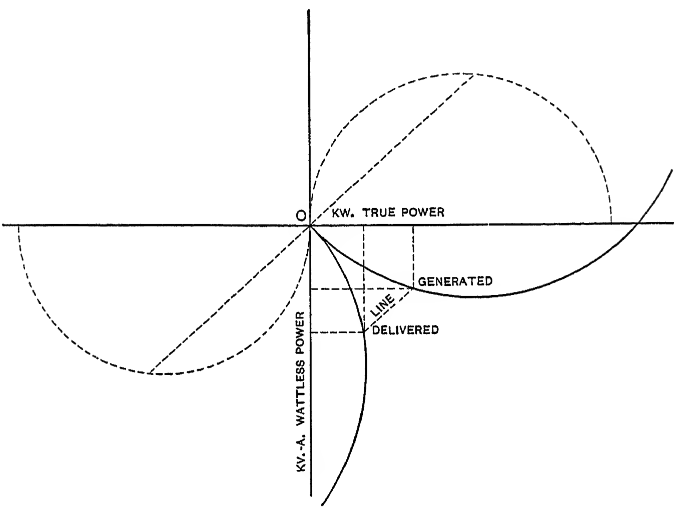


Fig. 5.—Power diagram—generated and delivered power

Interpreting (**45**), it is a circle of radius W_3 and center W_1, $-W_2$ passing through the origin. Similarly for a line with constant resistance, but variable reactance, (**45**) and (**28**) show that the centers of these various circles lie on a circle of radius $\frac{W}{2}$ and center at $+\frac{W}{2}$, 0. Fig. 5 is a power diagram for both the generated and delivered power. It consists of two equal tangent circles. From these it appears that with zero power delivered there is no wattless power at either end of line. With delivered power greater than zero there is always leading power required at the delivering end, but at the generating end it is

first leading then lagging after passing through a point of unity power-factor.

A transmission line of adjustable reactance carrying a constant current (at constant potential) will have a constant input and an equal constant output of apparent power, but the true power output may vary from zero to a maximum due to varying power-factor. The current and resistance being constant, the line loss will also be a constant; therefore, the efficiency will be a maximum with maximum output. The input is equal to output plus line loss, and will be a maximum at the same time. The true input is also equal to the constant apparent input, less a reduction due to any wattless component. Consequently, maximum input, output and efficiency occur when the wattless component at the generating end is zero. Under these conditions the relation between generated voltage, generated and delivered current, generated and delivered true power, line loss and efficiency are the same as for direct current. Consequently, power can be transmitted by constant-potential alternating currents, or by direct currents at the same efficiency provided the line reactance is suitable.

At first sight the maintenance of constant potential by increasing the line reactance and by adding a wattless component to the delivered current in order to overcome the increased reactance would appear to produce an increased line loss. That this is not the case may be seen from the following considerations. With direct current or with alternating currents as ordinarily distributed, the line loss produces a drop in voltage; therefore, an ampere is not capable of doing as much work when delivered at the end of the line as when generated. If then, by any device it is possible to counteract the voltage drop so that the delivered voltage is equal to that generated, then the same work can be done with a smaller number of amperes delivered. The device actually used for this purpose is a wattless current and the total line loss due to the smaller working current, plus the additional wattless current, is no greater than before. While this device has neither increased nor decreased the line loss, it has made the voltage regulation perfect, a result impossible with direct current. That is, leading wattless power introduced at the receiving end of the line does not necessarily increase the line loss, in fact it may decrease the loss while either leading or lagging wattless power entering the line at the generating end does increase the loss. No reactance can therefore

be found which will make the efficiency higher than that obtained when the wattless component is zero at the generating end. However, as with direct current, there are two currents each of which will deliver the same output with zero wattless power generated. One gives an efficiency of less and the other of more than 50 per cent. The latter, which gives the maximum efficiency for direct current, gives the true maximum for alternating current.

With a line of fixed reactance and with a load which gives zero wattless component at the generator, $w_3''=w_1''$ and $w_2''=0$, substituting these in (**44**) and reducing gives

$$w_1''=2\ W_1 \tag{46}$$

substituting the same in (**40**) gives

$$\frac{w_1{}^2}{W_3^2}=\frac{w_1'}{W_1} \tag{47}$$

and from (**46**)

$$w_1'=4\frac{W_1^3}{W_3^2} \tag{48}$$

substituting these values in (**35**)

$$w_1=2\ W_1\left(1-2\ \frac{W_1^2}{W_3^2}\right) \tag{49}$$

This condition of maximum efficiency generally differs from that of maximum output as defined in (**21**) unless $\frac{W_1}{W_3}=\frac{1}{2}$, as required by (**34**).

To show the effect of reactance on a line of constant resistance take F for the ratio of reactance to resistance.

$$F=\frac{X}{R}=\frac{W_2}{W_1} \tag{50}$$

The magnitude of the alternating constants W_1, W_2 and W_3 may be conveniently compared with the direct current constant W by taking the ratios $\frac{W_1}{W}$, $\frac{W_2}{W}$, $\frac{W_3}{W}$ which may be expressed

in terms of F. This gives a relation true for any line, the alternating short circuit power and its two components being a fixed percentage of the direct current short circuit power for any given proportion of reactance. The relations from (**26**) are

$$\frac{W_1}{W}=\frac{W_1^2}{W_3^2}=\frac{W_1^2}{W_1^2+W_2^2}=\frac{1}{1+F^2} \qquad (51)$$

$$\frac{W_2}{W}=\frac{W_1\,W_2}{W_3^2}=\frac{W_1\,W_2}{W_1^2+W_2^2}=\frac{F}{1+F^2} \qquad 52$$

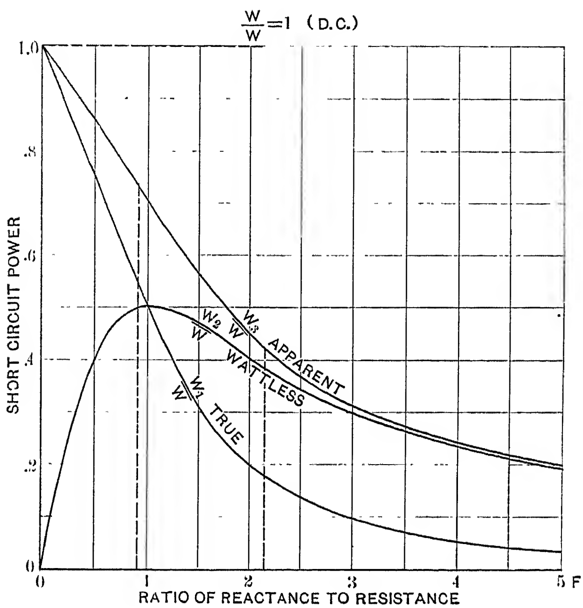


Fig. 6.—Short-circuit power

$$\frac{W_3}{W}=\frac{W_1}{W_3}=\frac{W_1}{\sqrt{W_1^2+W_2^2}}=\frac{1}{\sqrt{1+F^2}} \qquad (53)$$

These relations are plotted in Fig. 6 on which has been indicated the position of the constants of the No. 0000 line assumed above.

The maximum output for any given line reactance has been determined in (**21**); substituting the values from (**51**) and (**53**) gives

$$\frac{w_1}{W}=\frac{W_3}{W}-\frac{W_1}{W}=\frac{1}{\sqrt{1+F^2}}-\frac{1}{1+F^2} \qquad (54)$$

The relation between output and efficiency with different reactances may be determined for other than the maximum conditions already discussed as follows:
Transposing, squaring and adding (**35**) and (**36**) gives

$$w_3''^2 = w_3^2 + 2\,w_1\,w_1' - 2\,w_2\,w_2' + w_3'^2 \tag{55}$$

which with (**37**) gives

$$w_3'^2 = w_1'^2 + w_2'^2 = 2\,(w_2\,w_2' - w_1\,w_1') \tag{56}$$

Let P be the ratio of loss to delivered power

$$P = \frac{w_1'}{w_1} \tag{57}$$

Also

$$F = \frac{W_2}{W_1} = \frac{w_2'}{w_1'} \tag{58}$$

From (**57**) and (**58**)

$$F\,P = \frac{w_2'}{w_1} \tag{59}$$

Substituting these values in (**56**)

$$P^2\,w_1^2 + F^2\,P^2\,w_1^2 = 2\,(F\,P\,w_1\,w_2 - P\,w_1^2) \tag{60}$$

This reduces to

$$\frac{w_2}{w_1} = \frac{1}{2\,F}\,[2 + P\,(1 + F^2)] \tag{61}$$

Substituting from (**51**) and (**52**) in (**17**)

$$w_1^2 + w_2^2 = 2\left(w_2\,\frac{F}{1+F^2}\,W - w_1\,\frac{1}{1+F^2}\,W\right) \tag{62}$$

Or

$$\frac{w_1}{W}\left(1 + \frac{w_2^2}{w_1^2}\right) = \frac{2}{1+F^2}\left(\frac{w_2}{w_1}\,F - 1\right) \tag{63}$$

From (**61**)

$$\frac{w_1}{W}\left\{1+\frac{2+P\,(1+F^2)^2}{2\,F}\right\}=P \tag{64}$$

This reduces to:

$$\frac{w_1}{W}=\frac{4\,P\,F^2}{4\,F^2+[P(1+F^2)+2]^2} \text{ or } \frac{4\,P\,F^2}{(2+P)^2\,(1+F^2)+P^2\,F^4} \tag{65}$$

The maximum value of $\frac{w_1}{W}$ with P constant may be determined mathematically to be when

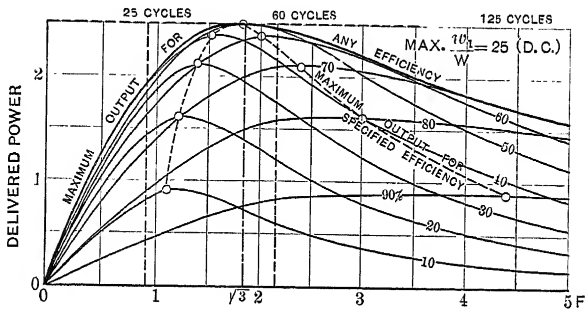


FIG. 7.—Delivered power

$$F^2=\frac{2+P}{P} \tag{66}$$

Substituting in (**65**) gives

$$\frac{w_1}{W}=\frac{P}{(1+P)^2} \text{ or } 2\,\frac{F^2-1}{(F^2+1)^2} \tag{67}$$

The latter corresponding to the result for direct current checks the conclusion already reached.

In Fig. 7 the results of equation (**65**) are shown graphically, also the points of maximum output at given efficiency and maximum output at given reactance.

A line with no reactance will absorb a very large amount of power if short circuited but will transmit no power at constant

potential. Give the line reactance and the power taken at short circuit is decreased but the line acquires the ability to transmit power. With increased reactance the short circuit power decreases continually, the ability to transmit power increases to a maximum and then decreases slowly. If the reactance is more than 1.73 times the resistance, the short-circuit power is actually less than the transmitted power as shown by Figs. 6 and 7 and the following table:

Line reactance	Short circuit power	Maximum transmitted power
F	$\frac{1}{1+F^2}$	$\frac{\sqrt{1+F^2}-1}{1+F^2}$
0	1.00	0.00
1	0.50	0.21
$\sqrt{3}$	0.25	0.25 (max.)
2	0.20	0.25–
3	0.10	0.22
4	0.06	0.18
∞	0.00	0.00

To obtain the greatest possible output over a line the reactance should be 1.7 ($\sqrt{3}$) times the resistance. It therefore appears that a high line reactance is favorable for transmission of large amounts of power by this system. Under short circuit, however, the line reactance greatly limits the amount of power that can be taken by the line. A short-circuited line may take less power than its full load. In other words, more power will flow into a line having no drop in voltage from generator to receiver than into one having full voltage at the generator and zero voltage at the receiver. On constant-potential systems of unlimited extent using high line reactance a short circuit would be a local matter, for one point may be short circuited without affecting the voltage except for a moderate radius and without concentrating any exceptional amount of power at the short circuit. Such a limitation on short circuits insures the continuity of the service as a whole, makes it safe to connect an unlimited amount of power to such a system (provided the sources are distributed) and sets a limit to the amount of power it is necessary to design switches to handle.

The same principle may be capable of further extension. Between large adjacent plants or between the two halves of a

very large plant an artificial line of reactance without resistance may be introduced which will limit the power which may pass on short circuit without preventing the interchange of power required for ordinary multiple operation.

From this point of view the characteristics of constant-potential transmission of power over lines of zero resistance (that is through reactive coils)are of interest. Fig. 8, a modification of the previous one with $W_1=0$ shows the relation. Let W_2 be the apparent power taken by the line with one end short circuited. From (**17**) the power transmitted is

$$w_1^2+w_2^2=2\ w_2\ W_2 \tag{68}$$

$$w_1^2=2\ w_2\ W_2-\ w_2^2 \tag{69}$$

$$\text{or}\ \left(\frac{w_1}{W_2}\right)^2=2\left(\frac{w_2}{W_2}\right)-\left(\frac{w_2}{W_2}\right)^2 \tag{70}$$

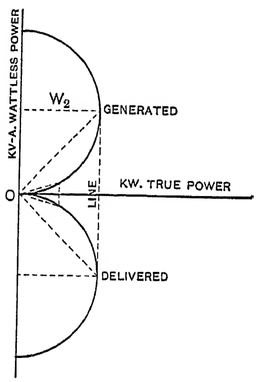


FIG. 8.—Power diagram —transmission through reactive coil

The maximum amount of true power which can be transmitted is $w_1=W_2$. The apparent power taken under this condition is $w_3=\sqrt{2}\ W_2$. The maximum amount of apparent power which can pass through the line with the two ends in opposite phase is 4 W_2.

Taking one-half the maximum as the normal rating of such a line it will at normal load take in addition at each end 27 per cent wattless power giving an apparent power of less than 104 per cent rating, that is a power factor of over 96 per cent, at the same time limiting the apparent power in case of a short circuit to 200 per cent rating or in the extreme case of the ends being out of synchronism and in opposite phase to 400 per cent of rating.

It has been shown that increased line reactance may actually increase the capacity of the line for transmitting power. The principle that line reactance is beneficial may be further extended by showing that adding reactance may also improve the efficiency of transmission. The greatest possible output over a line is obtained with a reactance 1.7 ($\sqrt{3}$) times the resistance but under these conditions the efficiency (as with direct current)

is only 50 per cent. For commercial purposes the efficiency must usually be higher. Taking an efficiency of 90 per cent for example and referring to Fig. 7 it will be noted that with increased reactance an increased amount of power can be transmitted. The maximum being reached when the reactance is 4.4 ($\sqrt{19}$) times the reactance at which point the amount is as great as for direct-current transmission.

An equivalent result may be reached with Fig. 7 from a slightly different point of view by considering the transmission of a fixed amount of power say 1/10 of the direct current short circuit $\left(\frac{w_1}{W} = 0.10\right)$. From this it appears directly that increasing the line reactance improves the efficiency.

Improved efficiency for a fixed amount of power delivered must signify a decrease in line loss which for a line of fixed resistance can only be due to a smaller current transmitted. Since the working current is delivered at a fixed voltage any decrease in total current must be in the wattless component. It may be concluded therefore that increasing the line reactance decreases the wattless power necessary for constant-potential transmission.

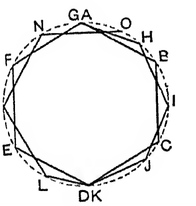
Fig. 4 illustrates the point in a somewhat different light. It shows that for any line reactance there is no wattless power at no load. To get power to flow over the line it must be fed with wattless power; a small amount permits a small amount of power to flow, a larger amount of wattless power permits more and so on up to a certain maximum. It shows further that as before found for a given amount of power delivered increasing the reactance decreases the wattless power necessary.

Briefly, we may say that line reactance makes a line opaque to the natural flow of power, that is, for delivering power at unity power-factor or for absorbing it at short circuit. However by artificially introducing a suitable wattless current the line becomes transparent to the flow of power for the time being. Remove the wattless current and the line again becomes opaque. Short circuiting the line at the receiving end automatically removes the wattless current and decreases the flow of power. Furthermore increasing the line reactance makes the line more opaque to the natural flow and within certain limits more transparent to the artificial flow as facilitated by a given wattless current.

The phase relations in a constant potential transmission system)f large extent are of importance. In the ordinary system of ransmission by direct or alternating currents as the power flows he voltage decreases, in this system the voltage also undergoes . change but it is a retardation of phase not a reduction of mag- iitude. Phase retardation may be of unlimited magnitude hereby fitting the system for unlimited extension.

Take the simple case of a single generating station feeding a ingle transmission line with substations at intervals. Call the)hase of the generating station O then that of the successive ubstations will be behind that of the generating station by .mounts increasing progressively by regular or irregular intervals .s for example according to the following assumed figures:

Generating station	*A*.	phase	0 deg.	
Substation	*B*.	phase	− 60	deg.
"	*C*.	"	− 120	"
"	*D*.	"	− 180	"
"	*E*.	"	− 240	"
"	*F*.	"	− 300	"
"	*G*.	"	− 360	"
"	*H*.	"	− 405	"
"	*I*.	"	− 450	"
"	*J*.	"	− 495	"
"	*K*.	"	− 540	"
"	*L*.	"	− 570	"
"	*M*.	"	− 630	"
"	*N*.	"	− 690	"
"	*O*.	"	− 750	"



IG. 9.—Voltage diagram of transmission lines

Fig. 9 is a vector diagram of the voltage phases of the several stations and the lines joining them. It is evident that the vector diagram is a polygon inscribed in a circle of radius equal to the nominal voltage. The polygon may be regular but will usually be irregular, it may be closed on itself but will usually be open either because incomplete or because the sides are not an exact submultiple of a complete circumference. If closed it ıay be so after one, two or more complete revolutions. The ›ltage at the stations are at the vertices, the sides representing ıe variation of the voltage along the line which it may be ›ted is always a minimum at the middle. The minimum being

lower as the phase difference between consecutive stations increases. While the maximum difference in phase between any two stations on a system may be of unlimited amount that between consecutive stations is limited.

If the instantaneous voltages, instead of the vector voltages were taken they would show the potential moving forward in waves from A to O. From A to G would be one complete wave length, from G to O would be one and one-twelfth wave lengths. The frequency of the wave would be that of the voltage used, its velocity would be variable depending arbitrarily on the distances and phase difference between adjoining stations.

Referring again to the vector diagram; points of coincident phase such as D and K and A and G are of especial interest. Being of the same phase and voltage they may be connected and no current or power will flow over the connecting wire. If another line ran from A to G by a longer route and entered G with a phase of $-$ 720 deg. then the two lines could be connected and (for the time being) no current would flow. It is analogous to connecting corresponding wires of two spiralled transmission lines, one with one and the other with two complete spirals.

Another case occurs where the phase retardation is not a multiple of 360 deg. but is a multiple of the phase angle of the system, that is of 120 deg. in a three-phase system or of 90 deg. in a two-phase system. Assuming that the system taken as an example is three phase and that another line runs from A to E and enters E with a retardation of only 120 deg. On testing out for phase it would appear that a phase of one circuit was in phase with b of the other and could be connected without flow of power or of current and similarly for the other two.

This phase relation would be stable only for a constant loading. As the load varies the phase relation will vary too. With all load off the natural condition of the system is with all points at phase O. Any interconnection between points having the same apparent but different actual phase relation as above discussed would cause the circulation of a short circuit current if all the load were taken off. However, once established, a system of indefinitely great extent while it would vary in load between certain limits would never return to a condition of zero load.

While it is possible and may be desirable to have a uniform potential over a network of reversible transmission lines, this condition is not essential. The fact that the potential may be higher at the receiving than at the generating end of a line has

already been referred to. Stated generally the relative voltage at the two ends of the line does not determine and is not material as regards the direction of transfer of power. Therefore, in a network the relative voltage of the different junction points may be arbitrarily fixed at any reasonable percentage above or below the nominal voltage and held there without preventing the transfer of power. That is to say, on a 11,000 volt system some stations may operate at 11,000 volts exactly, others at fixed voltages of 10,000, 11,500 and 12,000 simultaneously without regard to variation of load or to the direction of power transfer. Lines with their ends held at different fixed voltages are reversible but not symmetrically reversible, neither is the substation equipment strictly interchangeable. In developing a system with a view to indefinite extension, complete interchangeability of apparatus, and perfect reversibility of transmission would point to uniformity of voltage as the logical plan of development. The equations given have therefore been limited to true constant potential transmission, though as here pointed out the principles on which such transmission depends does not preclude an established 13,200-volt system being directly interconnected (without transformers or auto-transformers) with another established 11,000-volt system, each continuing to operate at its own fixed voltage. There are, however, disadvantages to such a connection which make it desirable to avoid it where the differences of voltage are not yet established.

The formulæ given neglect electrostatic capacity and leakage. They are applicable to those cases where the voltage is not high or the length of section is not great. By modification they could be extended to include effects of capacity and leakage. It may, however, be noted that it is not the capacity of transmission system as a whole (which may be very great due to large extent) but the capacity of the individual line section which affects the accuracy of the calculation. In a preliminary examination of the theory of constant potential transmission it is advantageous to omit consideration of line capacity because while capacity may in certain cases greatly modify certain results, it is line inductance alone and not line capacity which is essential for producing the results. Although lines have capacity as well as inductance and although in a general way reactances due to capacity and those due to inductance are physical quantities which can cancel each other like positive

and negative numbers, yet in a transmission line the capacity and inductance are related to the line in different ways (shunt and series respectively) and do not cancel but produce semi-independent results which are of a different nature. The capacity adds a component to the current, the inductance subtracts one from the voltage. In this method of transmission it is the inductive reactance which is of prime importance because that directly controls the voltage which it is the purpose to keep constant. The capacity reactance (or rather susceptance) of the system as a whole affects the amount of wattless current which it is necessary to produce at the several stations and substations, but as any amount necessary is supposed to be obtainable from suitable synchronous motors and generators, the capacity currents would be neutralized artificially whenever necessary at these points. On any section between two stations there would be a local effect which is however of only secondary importance.

Discussion on "Economic Limitations to Aggregation of Power Systems", Boston, Mass., February 17, 1911.

A. E. Kennelly: The paper is of great interest, both theoretically and practically. It assumes the existence of not merely transmission system, but rather of a system of such systems; that is, it presupposes a network of transmission and absorption of power, including a plurality of generating and delivery stations.

In the ordinary transmission system of to-day, we are accustomed to regard the problem of electric pressure regulation as a corollary of the ordinary direct-current system. We expect to have a drop of pressure between the generating station and delivery station of not more than, say, 10 per cent of the delivery pressure, at rated load. This is a natural habit of thought derived from direct-current practice. In order to enable such a 10 per cent limit of drop to be maintained, the power-factor of the load may have to be restricted to a certain range, and condensive reactance may have to be supplied, with the aid of over-excited synchronous motors, in order to succeed.

If, however, a large number of transmisson and delivery lines spring up in any territory, it is evident that they must tend to coalesce; unless actually incompatible, so numerous and powerful are the engineering advantages to be gained by merging them into a single network. Having developed such a network, the complexity of maintaining assigned percentages of voltage drop on the lines, under various conditions of load, or of maintaining assigned percentages of power-factor, is likely to become excessive, and the old method of regarding the matter is therefore likely to become untenable.

The paper suggests that, under such conditions, much simpler conceptions and modes of operation are to be found in maintaining constant effective voltage at all station switchboards, and in ignoring the power-factors of the various loads, except in so far as these may indirectly have to be controlled in order to secure constant voltage. The idea is that no power-factor meters need appear on the various switchboards, and that the switchboard attendants shall regulate entirely for constant line-voltage.

In the paper reference is made to the fact that current may be made to flow in such a system from a point of lower to one of higher potential. This, of course, refers to effective, or r.m.s., potentials; because we know that, at any instant of time, current can only flow from a point of higher to a point of lower potential; but that, owing to difference of phase, the r.m.s. of the potential at the load may be greater than the r.m.s. of the potential at the generating point, taking the whole cycle of alternating potential into consideration.

We also know that all transmission lines necessarily possess

magnetic reactance. If a lagging current flows over such a line, the drop of r.m.s. pressure, as between generator and substation switchboards, becomes exaggerated. If, on the contrary, every distinctly leading current flows, the drop of pressure may be negative, or the r.m.s. pressure may be higher at the substation switchboard. As an intermediate condition, if the current leads moderately, the apparent drop of pressure may be made zero, and the voltage at both switchboards will thus be the same.

The paper, therefore, calls for a system of inter-connected stations such that every load may be a suitable leading load. This means that adjustable condensive reactance must be supplied at each substation. It will not do to have mere non-inductive loads. A pure resistance load—a simple lighting load—or a load of 100 per cent power-factor, will not suffice. There must be a definite amount of lead in the load. The power-factor must be less than 100 per cent and leading, so as to produce neither rise nor fall of voltage at the substation switchboard. Consequently, a synchronous motor, of adjustable excitation, to act as a condenser, must be available at each substation where power is delivered. If the load is a purely lighting load, very little over-excitation will be needed in the synchronous motor of the substation, in order to maintain the required lead of current-phase, for constant line voltage at the switchboard. If, on the other hand, a heavy inductive load, is delivered, such as an induction-motor load, correspondingly powerful over-excitation will be needed in the synchronous motor. Variations of load will thus call for variations of excitation, to keep the switchboard voltage steady.

If there were no magnetic reactance in the line wires, the method here under discussion of reducing the apparent line-drop to zero could not be used. The paper points out that, up to a certain point, the presence of reactance in the line is useful, for the purpose of maintaining uniform switchboard voltages over the entire system. It is intimated, in fact, that extra reactance, introduced into the lines, may thus benefit power transmission. Loading a telephone line with artificial reactance is well known to be beneficial in the case of electric telephone transmission. The analogy at once suggests itself that if loading a line with reactance is beneficial in alternating-current telephony, the same plan may also be beneficial in alternating-current power-transmission. It must be remembered, however, that the effect of loading a telephone line is to increase its tension. It reduces the effective current and increases the effective voltage of transmission, and so reduces the $I^2 R$ losses, in essentially the same way that increasing the voltage improves the economy of power transmission. This is very different from the effect here considered of loading a transmission line, and there is no proper analogy between the two cases.

A suitable amount of magnetic reactance in the lines of a large power-network is likely indeed to be useful, as indicated in the

paper, for limiting the violence of short-circuits, and the distance to which their injurious influences can extend; but it is questionable how far loading lines with reactance may be carried with advantage on other accounts. In a direct-current line of total resistance R ohms, a working current of I amperes will effect a drop of pressure of $I R$ volts, which must subtract from the generator voltage to give the substation voltage. In an alternating-current line of total impedance Z ohms, an effective working current of I amperes must similarly produce $I Z$ volts drop. The impedance Z must always exceed the ohmic resistance and may greatly exceed it if there is much reactance in the line. Now, as shown in the paper, it is possible to swing the $I Z$ drop into such phase relation to the generator-end voltage, that the vector difference, or receiving station voltage, may be numerically equal to the generator end voltage; but the greater the $I Z$ drop, the greater will be the changes of voltage that variations of load will tend to effect; or, to express the same condition in another way, the closer and more cared for will be the adjustment of leading current and condensive reactance that the synchronous motor must produce. Moreover, the greater the reactance in the system, the more powerful the surge overvoltage in the system that a given disturbance will set up. Consequently, the principle of the benefit derivable from extra reactance in such a system should be received with caution.

The author of the paper is to be complimented upon the very interesting and beautiful geometrical theorems which he presents in the supplement. These theorems are restricted to the limitation, laid down as a postulate, that constant voltage is maintained at the stations on the line. If this condition is departed from a considerable deviation may be involved in the conclusions, in some practical cases. But, from a theoretical standpoint, and within this limitation, the results deduced are very interesting.

It is to be regretted that in a paper which bids fair to be long remembered, the term "wattless power" is employed. This criticism is directed solely to language used, and not to the facts which the language is intended to express. The term "reactive power" would be just as easily understood, and would give rise to no self-contradiction in terms, besides avoiding ambiguity. Reactive volt-amperes in an alternating current system are just as "wattful" as the volt-amperes that are delivered and recorded through time, on the watt-hour meters; except that the reactive power is developed in displacing energy within the system from one part of the system to another; while the delivered power is developed in displacing energy from inside the system to the consumer's apparatus outside the system. Delivered power is saleable, and reactive power is not saleable; but the commercial distinction should not interfere with the terms and concepts of the matter, as they are reflected in the mind of the engineer.

N. T. Wilcox: The cheapening of hydraulic development due to the lesser cost and large production of Portland cement and the ability to transmit successfully at voltages of 100,000 or more have made things possible to-day that were impossible a few years ago. We even hear rumors of higher voltages than those mentioned.

It seems to me of prime importance that in the development of these propositions, efficient and competent engineering talent be employed. If these large plants are developed along wrong engineering lines, the resultant mistakes crystallize as a permanent tax on the whole development. We may be able to get rid of bad management, but are seldom able to get rid of the charges following a badly engineered development.

E. A. Ekern: The constant potential system as outlined in the paper by Mr. Philip is an ideal system as regards voltage regulation. To obtain this ideal voltage regulation it presupposes a sufficient and ample control of the power factor of the load at all of the various points on a transmission system.

With the continued growth of the high-tension transmission systems has developed a continual battle on the part of the engineers operating these systems to maintain a reasonable power factor which is essential to good voltage regulation. Until recently the tendency has been to attempt to improve the regulation by increasing the voltage. Except for the larger systems distributing large quantities of power to central points a limitation to the increase of voltage has been found in the corona loss from the small sizes of conductor and in the operating difficulty of charging the high tension lines which require a very large charging current and consequently a large current carrying capacity in the generating stations. In spite of the increased voltage of transmission of some of the long distance transmission systems until they are operating under the above conditions of corona loss and large charging currents many are experiencing difficulty in obtaining good voltage regulation on account of the low power factor resulting from the extensive use of the induction motor which predominates the field of small individual drive.

Many transmission engineers are turning their attention from the problem of increasing the voltage which has been solved quite satisfactorily and appears to have reached its present limitation for smaller systems, and are devoting their energies to improving the power factor and devising an equitable basis of charging for energy depending on the power factor of the load and its influence on the transmission system. This is being done to such an extent that it is now quite common practice to charge additional for energy of a load having a lagging power factor and placing a premium on energy of a load having a leading power factor. An excellent system for a rational basis of compensation according to the character of load was outlined by Professor Hooper at the last meeting of the Boston Section

held at Tufts College. This system consisted of not only metering and charging for the kw-hr. of energy but also metering and charging for the kw-hr. of wattless energy according as to whether it is lagging or leading.

If a system can be obtained which places a premium on a satisfactory power factor so that it will be found desirable to control the power factor at the various points of loading a high-tension transmission system it becomes quite possible to obtain the conditions as outlined in Mr. Philip's paper and the constant potential system will then be realized.

Edw. N. Lake: Two or three of the preceding speakers have appeared to be of the opinion that the paper this evening applies particularly to electrification problems. It seems to me that it has a very much broader application than the electrification of steam railroads. It involves, to my mind, all of the uses to which power may be applied and is a most daring conception—that of a high tension network covering the whole country just as a 250-volt or a 600-volt network serves a very limited territory.

Electrification of steam railways will never become general until two of the fundamental ideas of Mr. Philip's paper can be commercially applied; *viz.*, uniformity and interconnection. Transposing into railway language, uniformity becomes standardization, interconnection corresponds to interchange. Electrification cannot be made attractive to the railway man until standardization and interchange are positively assured to him.

R. P. Jackson: Mr. Philip's paper outlines a system of power transmission or rather of power traffic which is of unusual interest. The possibility of many or all power producers and users pooling their interests and supplying power to a common fund or drawing from this fund as it were, to meet their immediate needs is in the nature of a banking operation with electric power taking the place of funds.

One point of note, however, is that while *watts* may be the commodity exchanged the medium of exchange must properly be *voltamperes*.

While a customer who fails to supply his own lagging current may be automatically penalized by a drop in his supply voltage, yet his load may be such as not to suffer greatly from this cause while another customer adjacent in line connection may be inconvenienced by such drop. There is, moreover, to be considered the effect on generator capacity.

Consequently the system of metering must either register in volt-ampere-hours or preferably in two separate records, one of true power and the other of wattless ampere-hours. This would permit a system of premiums and discounts to be used, taking into account the quality of the medium of exchange.

According to the method of regulation given by Mr. Philip a more equitable system of metering might be to measure the power and the integrated volt-seconds of variation up or down from a standard line voltage.

Then either a power producer or a power user could be penalized for variations from the voltage of the system.

Metering devices to accomplish these results, however, are not now available so far as we are aware. Metering problems are even now rendered difficult by the question of maximum demand and limitation of peak loads, and the introduction of the necessity of taking account of apparent watts still further complicates the matter. The other advantages of the system described by Mr. Philip are such, however, that, should the commercial application of it demand, suitable metering methods and devices would doubtless be forth-coming.

Another feature of interest is that line reactance is no longer a disadvantage but on the other hand becomes a necessity. It is even suggested that artificial reactance in the form of choke coils be inserted in series with the line for the purpose of giving the greatest power carrying capacity to the line. Substantial choke coils such as are often used to protect against lightning and similar high frequency oscillations could then serve two purposes and cease to be looked upon with suspicion on account of the drop incurred.

A paper presented at the 259th meeting of the American Institute of Electrical Engineers, New York, March 10, 1911.

COMMENTS ON FIXED COSTS IN INDUSTRIAL POWER PLANTS

BY JOHN C. PARKER

Certain features of the cost of power generation in small plants seem to be the subject of such varying ideas that it has been thought worth while to indicate a few of these features with the hope that a discussion of them may bring about a greater consistency of view among the members of the profession. The features presented in this paper will for the most part be confined to "fixed costs," comprehending thereunder those costs which are not closely a function of the energy output. While the latter elements of cost are more or less obvious during plant operation, the fixed costs are capable of but little modification or correction after a plant has been installed, and being a matter of economic rather than of technical judgment, and hence not always attracting the attention of engineers who may not have specialized in economic essentials, it is at once desirable that attention be called to them, and that they be given considerable weight during plant layout. The writer would call particular attention to the marginal principal discussed in the latter part of this paper as being one of critical importance, and one of those least commonly weighed by the profession.

Investment. As most of the fixed costs have to do with the *investment* made in the plant, it is worth while to call attention to a few of the component items of the investment. It is, of course, obvious that the purchase price of the machinery must be included. The writer has been surprised, however, to note in dealing with something over 300 industrial engineering propositions, that in many cases the preliminary estimate of the plant investment will stop at this point without giving consideration

to the cost of real estate, housing, to freightage and teaming, sometimes without attention to the labor involved in installation. Supervision is very often entirely overlooked, and yet engineering design and supervision are just as much a part of the cost of a plant as is the engineering design that is paid for when the purchaser lays down the purchase price for an engine or for a generator. It might seem superfluous to mention this almost obvious fact, did not the writer recall that in a recent consultation with a public service commission objection was made to carrying depreciation on the labor and superintendence involved in setting transmission poles, placing station machinery, *et cetera*.

Since the installation of a plant costing $10,000 or $20,000 will constitute a physical improvement to the property, it is obvious that the *tax* assessment will be increased thereby, and that this fact should be reckoned on in pre-estimating power cost. It is unnecessary, of course, to more than mention this fact in the way of a memorandum.

Insurance. The cost of carrying *insurance* is sometimes overlooked in pre-estimating power cost. It is obvious that this is just as much a part of the cost as coal and superintendence. It may not, however, be quite so obvious at first blush that something more than the insurance on the plant investment may have to be assessed against the plant, but on slight reflection this will be seen to be a possible, and in some cases, a very certain condition. If, for instance, the installation of a plant increases the fire hazard on the property as a whole, the net increase of insurance on the property should be assessed against the plant which has occasioned this net increase. In addition to the ordinary fire insurance there must be carried, in some form or other, accident and liability insurance, and this will vary with the nature of the industry for which the plant is installed. In a manufacturing plant the possibility of accident to plant employees only would have to be considered, whereas in a department store the patrons of the store would have to be covered as well. This expense and the fire insurance are existent whether such insurance is actually carried, or not, since a sum of the same order of magnitude as the insurance premiums must be laid aside to provide for such contingencies for which the insurance is carried.

Interest. The writer has found very few cases in which *interest* has not been considered in some form or other, but in

general he has found that not only the *engineers*, but the business men contemplating the plant installation—a class from which one might expect deep appreciation of such details—habitually underestimate the cost of borrowing money. Many details other than the merely nominal interest rate enter here, a fact readily recognized by any concern that has occasion to float bonds or preferred stock; and these details should, of course, be given their due weight in each case in determining what interest burden a plant will have to bear.

It is worth noting that very few business concerns have an unlimited borrowing capacity, in fact, any prosperous and extending business may be expected to closely approximate its credit limit, so that a further extension of obligations will definitely depreciate the total credit of the concern for borrowing purposes, thereby either hampering the borrowing of money or increasing the interest rate that must be paid. In such a case the part of the business so prejudicing the borrowing capacity should be compelled to carry the burden thereof itself, rather than to distribute the burden over the business as a whole, since this part of the business is responsible for and occasions the additional expense. For a fuller discussion of the principle underlying this, reference may be made to the already mentioned marginal principle appended to this paper.

Depreciation is the subject of as widely variant views as exist in any of the details of plant cost. The writer has found that in many cases the life of a plant will be estimated from the length of time that some plants have been in service. This seems to be an utterly untenable basis for calculation, since many an engine may be found to be operating at the end of 30 years from its initial installation without the fact of necessity proving that the depreciation rate should properly have been assumed as $3\frac{1}{3}$ per cent; it might be that the plant should have been scrapped 15 years previously. The desirable and proper life to assume for a plant is the length of time for which it can in all probability be *economically* run; in other words, depreciation should be predicated on the date at which the plant *should be* put out of commission, rather than the date at which plants *have been* put out of commission as a result of absolute failure to functionate. The time at which scrapping of any apparatus in any given plant should occur is that at which the reduced efficiency and the increased maintenance, renewal, and repair costs of that detail are great enough to justify the purchase of

new apparatus under the particular operating and business conditions obtaining.

It seems highly objectionable to take an average rate of depreciation and apply it to the power plant as a whole. The depreciation rate is considerably greater on boilers than it is on engines; considerably greater on engines than it is on buildings, and so on. If, then, a plant has a preponderance of those items which will deteriorate rapidly, the depreciation rate will be high, and *vice versa*. Each class of apparatus and construction in the plant should be multiplied by its own depreciation rate, and the aggregate of the products taken as the depreciation expense per year. This is not a particularly arduous task, since the apparatus will naturally group itself into a very small number of general classes.

An over estimation of depreciation rates should be guarded against, of course, and for this purpose a sum should be set aside each year, which, with the compound interest that it can earn, will at the end of the life of the various classes of apparatus in the plant pay for their replacement. On short life apparatus this is not an item of so much importance as it is on the classes of longer life. The propriety of so figuring amortization, irrespective of whether a proper sinking fund is allowed or not, is determined from the fact that if such sinking fund deposits are not made, the money that would have gone into them appears as a part of the earnings of the firm, and is paid out immediately to the stockholders, who thereby have the use of the money which, however employed, should earn the same compound interest as would be earned by the money if placed in a sinking fund.

In this discussion of depreciation no attempt is made to indicate where maintenance, renewals, and repairs should cease, and depreciation begin. It is for each engineer to determine for himself how far he can afford to go in making these operating expenses avert the day when a plant will have to be scrapped. Once having determined the most economical relation between these operating expenses and the proper life to assume for the plant, both they and the amortization fund should be included in the pre-estimate of the power cost.

Obsolescence. If by this term we mean the supersession of the apparatus initially installed by a more efficient type which may develop before the initial apparatus has reached the scrapping point, it is not an important charge, even though the supersession may take place under stress of competition, since such

supersession will not be undertaken unless the new apparatus can save enough to justify the expense, in which case these savings must themselves take care of so much of the new investment as is not already covered by the sinking fund which should have been provided by the old plant. Obsolescence, therefore, has essentially no existence for private power plants even under stress of competition.

The case is somewhat different where the business of a concern is power sale. In this case the "quality of power," as well as the cost of its production, is a vital element in competition, so that the development of a new type of apparatus which will improve the quality of the power supply may render existing machinery obsolete, and under stress of competition from privately owned plants, or from a competing utility company, may force supersession, as, for instance, the development of 60-cycle apparatus forced many of the higher-frequency generators out of commission before the termination of their natural life.

In one respect it may be desirable to carry an obsolesence fund even in an industrial plant. The existence of such a fund renders more readily possible the supersession of the obsolete apparatus when economically justified—it has in fact the effect of rendering fluid the plant investment at the expense of the earlier years of operation before obsolescence may arise, and when the stress of competition may be less burdensome. The managers of the industry must themselves consider how much weight they will give to this consideration by attempting to prognosticate their future borrowing capacity for supersession purposes.

In case of the supplanting of a private plant by a public service supply, or of one private plant by another, the new plant will have to carry its own depreciation burden, and in addition, the portion of the older investment which has not already been provided for. The convenient way of considering this is to calculate what the sinking fund on the old plant should have amounted to on the date of supersession, and to credit the new equipment with this, and to then compel the new equipment to carry the burden of the old throughout the life of the new equipment, together with its own proper depreciation burden.

Supervision falls under the "marginal" principle referred to above. Briefly stated, this principle is that, if any part of a business requires time, material, or investment which could have been utilized in any other part of the business, the cost thereof

should be taken as what such time, material, or investment would have earned if applied to the most profitable part of the business which is still capable of extension. If, for instance, a power plant requires during installation, regular operation, in accounting, and during period of disability, 20 per cent of the time of the manager of the industry; and if the time of the manager expended in works supervision, supervision of sales, or any other detail proper to the industry, would increase the profits of the concern at the rate of $10,000 per annum, it is proper to charge the power plant with $2,000 a year for supervision.

In general the magnitude of power generation by a factory plant is not great enough to make it possible to employ or to attract a $2,000 a year man to supervise the plant operation, and yet many such plants actually deflect from the earnings of the industry by the distraction of the manager's attention a sum considerably in excess of such an amount. Failure to properly weigh this principle at the inception of the power plant installation may materially hamper the operation of the firm. It may be said that this principle presupposes capacity for extension in the various activities of the concern, which capacity may not be realized in fact, but it is pretty generally the case that a man who is fit to be at the head of any manufacturing or mercantile enterprise is about the busiest man in the concern, and that he has not any excess of leisure for devotion to the legitimate business of the concern. It is almost impossible to conceive any business incapable of extension by proper commercial attention to the discovery of new avenues for the output by proper advertising skill, or incapable of improvement in production processes by skilled attention directed to the processes of the enterprise.

Fair Profit. No man running a department store would think of putting extra capital into the china department where, in the nature of things, the turnover is small and the profits limited, if the clothing department, with a turnover of the stock thirty times per year, was not carrying a maximum business obtainable. Such a merchant would study his business and place each thousand dollars where it would earn the greatest profit, and would figure that the deflection of $1,000 from a department that could earn $300 per year, to a department that could earn only $100 per year, had actually cost him in the loss of profits $200 per annum. This is a tacit recognition of the mar-

ginal principle. If, then, an enterprise is making a net profit of 10 per cent per annum on the average—and not less and probably more than this on certain details of the business—there is manifestly at least a 10 per cent per annum loss in the investment of money in a power plant—or in any other part of the business—if the money earns only the fixed items of taxes, insurance, interest, depreciation, and supervision, and the amount lost is just what could have been gained by the investment of such a sum in the most profitable part of the business. How much this shall be must be determined for each individual plant, but for the sake of fixing an idea of magnitude the writer would say that he recently encountered two instances in which the proprietor of an establishment figured, as a proper charge against his contemplated power plant, at least 10 per cent of the initial investment to cover "fair profit."

It is, of course, obvious that if the business is not capable of further extension, and if the investor knows of no such other business, or if the credit of the business is so good as to render it possible to borrow without difficulty enough funds to take care of all possible extensions, and to still have enough to install a power plant, the plant would not have to carry a more than nominal fair profit burden. Such a condition, however, is not at all a usual one, and will, therefore, have to be reckoned with in but few cases.

Building space and real estate come under the same marginal principle. It is not uncommon to hear the statement made that there is a certain amount of space that is wasted anyhow, and that might as well be used for power plant. The statement is correct where injudicious over-purchase has been made, or where excessive purchase has been compelled in order to secure what land was desired. But, with this one exception aside, it is not at all proper to underestimate the rental value of the space. In the case of a mercantile establishment, for instance, the basement space is often used for boiler and engine plant room. This is permissible if there is no other use to which this space can be put, but it must be remembered that if this space is rendered useless for storage purposes, storage must be effected in the least desirable part of the establishment then remaining, thereby cramping such space and perhaps forcing an overflow into still more desirable space. The fair rental value must therefore be assessed as part of the annual cost of maintaining the power plant.

Appendix A

The marginal principle is much broader in its application than the subject matter of this paper, bearing as it does not only on matters of economics, but on many more strictly technical matters. The writer has found many cases where average or mean figures have been used in discussing various phenomena, and where conclusions arising from such use of averages were practically meaningless, yet not positively invalid.

For example, it may have been determined that refinements may be introduced into the construction of a hydroelectric plant whereby its capacity may be extended, and the degree of such extension may have been fixed on the assumption that it is worth while to spend, say, $150 per horse power for the development. A not uncommon practice is to design a plant with such refinements up to the point where the average cost per horsepower is $150. As a matter of fact, this would result in an over-development of the refinements, as will be seen in the sequel.

On a little consideration of our example it will be clear that the first horse power developed would reach a very high figure, indeed; that thereafter, capacity might be developed at progressively lower cost per horse power, especially if the development were concentrated in few units, but that a point will be reached where, owing to the difficulty of securing additional capacity through storage, enlarged pipe lines, more expensive turbines, *et cetera*, the cost per horse power will again increase. It is clear that if the average cost per horse power is only $150, and the cost of the first few horse power developed considerably greater than this, the cost of a certain part of the capacity must have been below the average figure of $150. It is further clear that the increasing cost of capacity at the point at which development is stopped of necessity entails a cost per unit greater than the average figure, so that the cost of such a unit at the point of termination of development will be above the average, and that such a unit is therefore a disadvantageous one to add. With this illustration we pass to a general discussion of the marginal principle.

The margin may be defined as the point at which development of an enterprise or of a physical construction is stopped. As a matter of economic expedience, the last unit of development added, that is, the unit existing at the margin, is called the marginal unit; and for a proper appreciation of the proper point

at which development should cease, we must look to the marginal unit and determine whether the cost of, or the advantage from this unit justifies its undertaking. It is unfair to the marginal unit, and economically fallacious to load onto it the burden of the disadvantageous initial unit on the one hand, or to credit it with the virtues of the intermediate units on the other.

Referring to Fig. 1, where, for example, we have plotted the investment in an enterprise as abscissæ, and the profit from such an investment as the ordinates, we observe that by projecting the curve back to zero investment, we have a condition where negative profits would ensue, that is, initially the business is a losing concern, since, with no business whatever transacted, the cost of operation constitutes a total loss. As the business

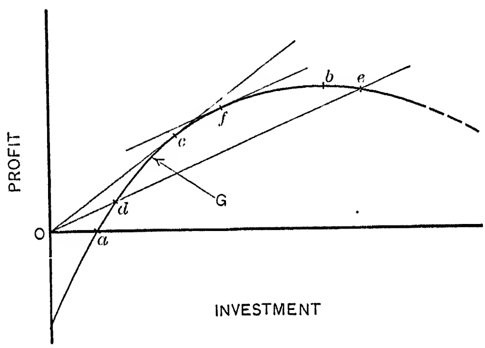


FIG. 1

develops, income begins to accrue and the loss is minimized. At the point a the volume of business and the investment therein have reached such a point that the business is no longer a losing venture, as the term is ordinarily accepted, but it is making no return over the interest, depreciation, and other such obligations. Beyond this point profits steadily increase to a point b, where, owing to any one of many possible conditions, such as over-saturation of the market, and the consequent reduction in selling price, or to the organization having become top-heavy, the total profits no longer increase. Beyond this point a decline in profits obtains. The point c of tangency of a straight line drawn through the origin is the point of maximum ratio between profit and investment, but this point is not of necessity the point at which extension of business should cease, any more than is b

the point of maximum aggregate profit. Drawing line $O\,e$, the tangent of whose angle of slope represents the fair business profit with which the promoter of the enterprise would be satisfied, we note that it has two intersections with the curve, one d, the other, e. It is manifest that the curve might lie so low as to be tangent to this line, or actually drop below it. In the latter case the business would not be attractive as an undertaking since the promoter can find more satisfactory investment for his capital. If, however, the curve intersects the fair profit line in two points, such as a and e, these points mark limits within which the business can be carried on without being undesirable as a whole. The slope of any line drawn from the origin to any point G between d and e represents the average profit per dollar invested when the business has been carried to the point G. It is manifest that if the point G is moved up to e the business will still be paying the fair ratio of profit to investment, and it might at first blush seem that e is the proper point up to which the investment and the business should be extended. This is not correct, however, since, while the *average* profit of the investment is still attractive, it is evident that the point has been reached where the profit on additional investment is very low, or, as in the special case in the figure, less than zero; that is to say, each dollar put into the business beyond the point b is making its return at the expense of the previous dollars put in, and may actually in itself be a losing venture. The proper point at which to have stopped development would have been f, the point of tangency of a line drawn parallel to $O\,d$, since up to f each dollar put into the business has been earning more than the fair business profit. At f only the fair business profit is earned; beyond this point less than the fair business profit is earned on each dollar invested.

From the above we see that the highest ratio of total profit to total investment obtained at the point c, but that the extension of the business should not have been stopped here; and again that it would not be advantageous to extend the business to the point e, where the ratio of total profits to total investment—in other words, the average return— is yet above the fair profit with which the promoter will be content; but that the point at which to stop development is that where the marginal investment produces a marginal profit of not less than the fair profit which will satisfy the promoter. Mathematically expressed, this means that the first derivative of the profit with respect to the investment must equal the fair profit ratio.

Specific applications of this principle have been referred to in the body of the paper in considering the liability and fire insurance cost due to the adding of a local power plant to an enterprise, in which case the local power plant constitutes the marginal investment, and where we are concerned with a cost function rather than with a profit function. A similar marginal investigation must be made in the case of the interest cost involved in the addition of a power plant to the concern, rather than a consideration of the average rate of interest, which will have to be borne by the enterprise after the power plant is installed. As previously pointed out, the applications of the marginal principle are various and have to do as well with the technique as with the economics of engineering effort.

Appendix B

For the purpose of fixing ideas as a basis for discussion, the following equations are submitted as representative of a group of methods of taking care of amortization. It is to be understood that there are various methods of providing for this fund, and that much is to be said in favor of each one as contrasted with the others. The method here presented distributes the amortization uniformly over all the years of life of the plant, but is not of necessity an expression of the actual physical rate of deterioration. It is assumed that the deposits into the amortization fund are made semi-annually, and that they draw interest at a fair market rate, compounding semi-annually. It is assumed that the amortization funds are invested where the risk, both physical and financial, will be the same as in the investment covered.

Let $\frac{a}{2}$ = semi-annual amortization rate.

$\frac{i}{2}$ = semi-annual interest rate on amortization fund.

n = number of years of life.

P = principal sum invested.

At end of first half year there will be deposited in amortization fund $P\frac{a}{2}$

which at the end of the rth year will have compounded to

$$P_1 = P\frac{a}{2}\left(1+\frac{i}{2}\right)^{2r-1}$$

and the second semi-annual deposit to

$$P_2 = P\,\frac{a}{2}\left(1+\frac{i}{2}\right)^{2r-2}$$

There will have been $2r$ such deposits of total amount

$$\sum_1^{2r} P_q = P\,\frac{a}{2}\left\{\left(1+\frac{i}{2}\right)^{2r-1}+\left(1+\frac{i}{2}\right)^{2r-2}+\;\ldots\;\left(1+\frac{i}{2}\right)+1\right\}$$

$$= P\,\frac{a}{2}\,\frac{\left(1+\frac{i}{2}\right)^{2r}-1}{\frac{i}{2}} \tag{1}$$

When $r=n$; that is, at the end of life we should have

$$P=\sum_1^{2n} P_q = P\,\frac{a}{2}\,\frac{\left(1+\frac{i}{2}\right)^{2n}-1}{\frac{i}{2}};$$

$$a=\frac{i}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{2}$$

Substituting this in (**1**) we have

$$\sum_1^{2r} P_q = P\,\frac{\left(1+\frac{i}{2}\right)^{2r}-1}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{3}$$

the amount of the amortization fund.

The unamortized part of the principal sum then is

$$P-\sum_1^{2r} P_q = P\,\frac{\left(1+\frac{i}{2}\right)^{2n}-\left(1+\frac{i}{2}\right)^{2r}}{\left(1+\frac{i}{2}\right)^{2n}-1} \tag{4}$$

Equation (**1**) above gives the accumulated amount of the amortization fund at any time during the life of the plant. Equation (**2**) gives the method of arriving at the annual amortization rate. This must be determined to substitute in equation (**1**) for its solution. Equation (**4**) gives the net burden that would have to be carried by any new installation in case of the supersession of an older one.

These equations in the case of any numerical calculation become much simpler than they appear in the literal notation; for example, in the case of a plant of 20 years' life, the amortization fund for which draws interest at the rate of 6 per cent per annum, equation (**2**) would become

$$a = \frac{0.06}{1.03^{40} - 1} \tag{5}$$

and equation (**1**) at the end of 7.5 years takes the form

$$\sum = P \frac{a}{2} \frac{1.03^{15} - 1}{0.03} \tag{6}$$

and equation (**4**) gives the unamortized debt as

$$P \frac{1.03^{40} - 1.03^{15}}{1.03^{40} - 1} \tag{7}$$

Appendix C

As an illustration of the operation of a few of the principles laid down above, the author appends figures presented to and endorsed by the owner and manager of a large mercantile establishment. The plant contemplated was to aggregate 150 kw. of generating capacity, divided between a 100-kw. and a 50-kw. direct current generator. The figures used are in large part based on the manufacturer's quotations and guarantees, and for the remainder, on experience derived from investigation of something over 300 small industrial plants, and are felt to fairly represent average conditions in plants of this character.

Table 1 shows the distributed costs, and the method of arriving at the amortization rate. Building and real estate are not included, since the plant was to be installed as a basement plant, the fair rental value of which is assigned in a later tabulation.

TABLE I

Item	Cost	Life	Amortization	
			Rate	Amount
		years	per cent	
Engines	$4,195	20	2.67	$112.00
Boilers, stokers and breeching	6,200	20	2.67	165.54
Stack	1,000	30	1.23	12.30
Generators and switchboard	4,700	25	1.78	83.66
Boiler auxiliaries	620	12	5.82	36.08
Piping	2,150	20	2.67	57.40
Foundations	300	20	2.67	8.01
Coal hoist	600	10	7.45	44.70
Aggregate	$19,765			$519.70
Mean			2.63	
Freight and rigging	500		2.63	13.15
Total	$20,265			$532.85

The marginal interest was assumed at 6 per cent. This is undoubtedly low for the specific case in point, since the enterprise was already limited in its borrowing capacity. The plant owner approved the fair profit ratio as being the minimum with which he would be content.

TABLE II

Marginal interest	6.00 per cent
Amortization	2.63
Taxes and insurance	3.00
Fair profit ratio	11.50
Aggregate	23.13 per cent

Careful calculation of the heating requirements of the building were made, basing them on the usual commercial operation of the heating systems in buildings of this nature.

As another illustration, the following figures derived from actual operation of a 120-h.p., four-cycle, two-cylinder, horizontal, single-acting, 200-rev. per min. gas engine and suction producer plant are presented. The fuel and water consumption may appear high; it is noted, however, that these figures are derived from the actual total consumption during six months commercial operation, and that the kilowatt-hours are the actual record by the switchboard meters of the net kilowatt-hours usefully delivered to the plant. Were the figures given in terms of indicated horse power-hours, they would have been materially lower, as a result of the elimination of energy required to operate auxiliaries. It is to be noted that in the balance sheet coal, water, and labor for heating the plant, and labor, supplies, and

TABLE III

............COMPANY

BALANCE SHEET

R. R. & L. Co. Electric Service-Heating from ...... Company Boilers

*Coal**

For heating. Based on 10 lb. evaporation. Day coal...............280 tons
Night coal..............231 "
Banking coal............ 20 "

Total...............531 "
Cost @ $2.60.................$1380

Ashes

Ash, 12 per cent. Total ashes 64 tons removal cost @ 25c. per ton.......................... 16

Labor

1 fireman 52 weeks @ $15..$780
1 " 20 " @ $15.. 300
1080

Supplies and Repairs

$0.794 per h.p. per year 200 h.p. installed.................... 160

Water

Assume 10 per cent loss in system cost @ $0.012 per 1000 lb....... 12

Electric Service

Present maximum demand....107 kw.
Estimated future maximum demand.......................140 kw.
The maximum and kw-hr. used each month for the past year have been increased by the ratio of 140 to 107

Estimated cost

Month	Kw-hr. 107–140	With discount
June	15980	$493
July	14850	365
Aug.	15270	399
Sept.	12540	401
Oct.	20820	535
Nov.	27450	610
Dec.	32800	655
Jan.	27420	605
Feb.	25230	581
Mar.	20720	541
Apl.	20700	540
May	19530	534
	253310	$6259

Total...................... 6259

Elevator Service

Present installation, estimated cost.......................... 415

Fixed Charges

Estimated value of heating plant $3,200
Fixed charges @ 25 per cent... 800

Manager's Time

And clerical expense.......... 25

Credit to Balance............ 2816

Total...................$12,963

*Best possible practice, purposely assumed conservatively.

Isolated plant

Fuel

253,000 kw-hr. @ 6.5 lb. coal 823 tons
Banking coal................ 58 "

Total...................881 "
Cost @ $2.60 per ton.......... $2290

Ashes

Ash, 12 per cent. Total ashes 100 tons. Removal cost @ 25c. per ton..................... 25

Labor

1 day engineer @ $21 per week
1 night " $17.50 "
1 fireman $15 "

Total...........$53.50 "
All labor on for 52 weeks
Total cost per year............. $2780

Supplies and Repairs

Cost per year per boiler-h.p. installed $1.22. Cost of 300 h.p... 366

Water

10 per cent loss during winter, and exhaust wasted during summer
Cost per year................. 60

Emergency Service

At 250,000 kw-hr. per year, av. per day is 800, av. per hour 33.
Assume 4 days shut-down per month, at ⅓ load or 11 kw. for 100 hr., a total of 1100 kw-hr. Assume max. demand at twice the average.

$$\text{Hours use } \frac{1100}{22 \times 26} = 1.9$$

Rate 7.1 cents.
Cost per month................. $78
" " year................. 936

Elevator Service

Present installation, estimated cost.......................... 415

Fixed Charges

Estimated cost of plant $19,200
Fixed charges @ 23.13 per cent. 4,441

Manager's Time

⅓ hour daily of 6-hour day @ $12,000 per year............... 1,000
Clerical expense, 1 hour daily, 300 days per year @ 50c........ 150

Rental Value of Space

500 sq. ft. @ $1.00 sq. ft...... 500

$12,963

fixed charges on the motor-drive are carried at zero, since it so happens that all these charges were carried as separate charges in the actual case of the gas engine plant, and they have, therefore, been eliminated from both sides of the balance sheet. Table IV represents the fixed charges, and Table V the balance sheet for this special plant.

TABLE IV

Investment in engine, generator, producer, switchboard, auxiliaries, and building, $11,000.

Average life (above), 12 years	
Amortization rate	5.81 per cent (6 per cent compounded semi-annually)
Marginal interest	6.00
Taxes and insurance	3.00
Fair profit ratio	10.19
	25.00 per cent

TABLE V

BALANCE SHEET

R. R. and L. Co. Electric Service

Coal

Water

Labor

Supplies

Electric Service

Month	Kw-hr.	Net Bill	
Jan.	11,860	$315	
Feb.	11,860	315	
Mar.	9,320	266	
Apr.	9,320	266	
May	7,920	247	
June	7,920	247	
July	9,320	266	
Aug.	9,320	266	
Sept.	9,320	266	
Oct.	9,320	266	
Nov.	11,860	315	
Dec.	11,860	315	
Total	119,200	$3350	$3350

Fixed charges

Manager's Time

Credit to Balance............3678.88

Total......................$7028.88

Isolated plant

Coal
119,200 kw-hr. @ 4.6 lb. coal per kw-hr. =275 tons @ $3.10.......$852.00

Water
119,200 kw-hr. @ 27.2 gal. per kw-hr. =434,000 cu. ft. @ $0.98 per 1000......................425.00

Labor
One engineer, 52 weeks, @ $22 1,144.00
Helper, 2 hours per day, 150 days =300 hours @ $0.30....... 90.00

Supplies
Oil, waste and supplies........265.00

Emergency Service

Month	Kw-hr.	Net bill	
Jan.	2141	$150.73	
Feb.	1263	95.99	
Mar.	211	20.00	
Apr.	55	20.00	
May	124	20.00	
June	258	20.64	
July	260	20.80	
Aug.	206	20.00	
Sept.	286	22.88	
Oct.	149	20.00	
Nov.	732	58.56	
Dec.	416	33.28	
Total	6101	$502.88	502.88

Fixed Charges
Investment in plant, $11,000
Fixed charges @ 25 per cent...2,750.00

Manager's Time
One hour daily, 10-hour day @ $10,000 per year..............$1000.00

Total......................$7028.88

A paper presented at the meeting of the Toronto Section, A. I. E. E., January 13, 1911, and also at the 259th meeting of the American Institute of Electrical Engineers, New York, March 10, 1911.

THE COST OF INDUSTRIAL POWER

BY ALDIS E. HIBNER

It is hardly necessary to call attention to the rapidly increasing importance of industrial engineering subjects, a condition which has made possible the presentation of a paper on such a heretofore relatively unimportant subject as the cost of industrial power. To-day one can scarcely pick up a technical magazine without finding some article on an industrial engineering subject. The comparatively recent growth of this activity is evidenced to some extent by the fact that the Industrial Power Committee of the A.I.E.E. has been in existence only three years.

The editor of a technical magazine recently commented upon the slowness of the industrial world in recognizing that organized manufacturing was essentially an engineering proposition and that the industrial engineer was quite different from an electrical or mechanical engineer. The writer went on to point out that the distinguishing features were chiefly the economic and human elements of the problem.

I know of nothing which will illustrate more vividly these distinguishing characteristics than a five minute talk with a manufacturer on the subject of power. Nearly every manufactured article requires the use of power for the completion of at least one step in the process. Almost all articles require power for every step of the manufacturing process. This results in all manufacturers having some experience with the cost of power, and there are just as many opinions on the cost of producing power as there are manufacturers.

The economic features of the problem are quite clear. Every power user wishes to obtain his power at a minimum cost.

The introduction of the human element, however, quite often produces far different results. I have in mind one manufacturer who was so anxious to obtain his power (representing about 2 per cent of the cost of production) at a low cost that he neglected his legitimate business. The result was a loss of considerable magnitude in his business and a cost of power 38 per cent higher than the cost at which his power could have been purchased from a power company.

Another example of the importance of the human element, and what it involves in the popular misconception and ignorance regarding the cost of power, is given by the manufacturer who maintained that his gas producer plant was turning out power for $15 per horse power-year, and that water power at $20 was of no interest. A test on this plant showed a cost of $75 per horse power-year.

These examples are not exceptional or exaggerated aspects of the condition that exists among the average power users. The manufacturer, as a general rule, does not know within an accuracy of 100 per cent how much his power is costing per unit. He knows how many tons of coal he is purchasing each year, and the wages of his engineer and fireman, but he does not know how many horse power-hours have been produced.

A little consideration will demonstrate that this is not a surprising state of affairs. A concern is incorporated for the purpose of making shoes, or candy, or stoves. The manager is chosen for his knowledge and experience in the production of these articles. The superintendent of a shoe factory knows how to place a shoe on the market that will sell in competition with other makes of shoes, and, at the same time, pay dividends to the stockholders. If he is doing this he should have little time to devote to the manufacture of kilowatt-hours.

One would suppose that the manufacturer himself would be the first to recognize this fact and employ a consulting engineer to advise him in technical matters, but such is not the case. I know of one manufacturer who signed a contract for a power plant, costing $40,000, upon his own inexperienced judgment and the advice of the salesman who sold him the plant. Later investigation of this contract showed that, for cleverness in concealing the real facts, it would put to shame any shell game on record.

Sometimes manufacturers retain consulting engineers on the basis of a percentage of the cost of the plant if it is installed.

The dangers of such a practice are quite evident, as it is asking a good deal of human nature for a man to lose a neat commission on the sale of a plant by recommending the purchase of power. The manufacturers themselves are largely to blame for this practice, as they persistently refuse to pay an adequate fixed sum that will obtain for them the services of the best engineers.

Unfortunately the engineering profession, like that of the medical and the legal, has its quacks, and a manufacturer has to take the same care in selecting his engineer that he uses in selecting his physician. It is to be hoped that the present agitation of this subject will result in some method of eliminating this difficulty.

At present it is a too common practice for a man, who tells you that his own business has been developed by years of experience and study of conditions, to spend two weeks visiting this or that plant with a salesman, and, at the end of that time, thinks he has a thorough knowledge of the power problem. In fact he may go so far as one manufacturer and get you off in a corner and whisper in your ear that gas producers are going to shut down the water power plants.

A manufacturer can no more trust his business judgment in the purchase of a power plant than he can trust it to perform a surgical operation. The question in either case is one of technical knowledge as well as economics. The man who paid $40,000 for his power plant was an experienced business, man, but he honestly thought his power was guaranteed not to cost over one cent per kilowatt-hour, and did not notice that the sum set aside to cover interest, depreciation, insurance and taxes represented less than three per cent on the investment. Neither did he notice that the amount allowed for coal did not include charges for banking his boilers over night, and that in spite of this chicanery the contract, on the face of it, showed a cost of one and one-half cents per kilowatt-hour.

In view of this state of affairs, I believe considerable benefit may be derived by an outline of the different factors to be considered in the cost of producing power and a general discussion of the same.

The cost of producing power by large central station plants has been quite fully discussed by the Institute, but, while some of the principles involved are the same, there can be no direct application to the small industrial plants. In the one case we are dealing with stations of several thousand horse power ca-

pacity, in the latter with a plant of a few hundred. The central station is organized for the manufacture of electric power and the plant location is chosen with the object of producing power at the lowest possible cost. The industrial plant is organized for the manufacture of shoes, or what not, and other considerations are more important in its location. The former has every possible advantage in favor of cheap power, the latter very often everything against cheap power. There are other considerations which make the problem quite different, such as the use of steam for heating and industrial processes.

It is not at the present time, as formerly a question of electric drive versus mechanical drive, for nearly all the new private plants are electric. What the manufacturer wants to know is, "shall I purchase my power from a power company, or are my conditions such that I can produce it cheaper myself?" It is some of the factors entering into a solution of this question that I wish to discuss in this paper. Every factory has conditions peculiar to itself which require special attention and prevent any general deductions. This does not mean, however, that the solution of a typical case will not be of value in showing the relative importance of the different factors.

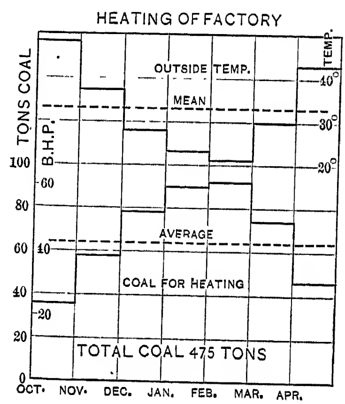


Fig. 1

There are in general three factors involved in every industrial power problem; the investment charges, operating charges, and the cost of heating or use of low pressure steam. The investment charges are understood to cover the interest, amortization, insurance, taxes, and profit on the capital invested in the plant. The operating charges include coal, labor, repairs, and supplies. The cost of heating is the investment and operating charges of the boiler plant necessary for heating the building and supplying steam for manufacturing processes.

A typical example of the conditions ordinarily found, we will say, is the Blank Shoe Co. which has outgrown its present quarters and has decided to build a new factory and eventually double its output. The new building is to be of brick, four

stories high, 250 ft. (76.2 m.) long and 60 ft. (18.2 m.) in width. This gives a total of 60,000 sq. ft. (5574 sq. m.) of floor area and a content of 750,000 cu. ft. (2023 cu. m.).

One of the first things which must be determined before starting construction is whether power will be purchased or supplied from a private plant. The first step in the solution of this problem is to determine the cost of heating the building. A heating plant is necessary in any case, as the conditions of manufacture are such that the temperature of the building must be kept above fifty degrees during the winter months.

Fig. 1 shows the mean monthly temperatures for the seven winter months at Toronto. The lower curve gives the coal per month necessary to heat the building to a temperature of 65 deg.

TABLE I

Heating Plant Investment.		
Boiler, piping and auxiliaries, (A)	$1,500.00	
Building and stack, (B)	2,500.00	
Total investment	$4,000.00	
Fixed Cost		
Interest 6 per cent on $4,000	$240.00	
Insurance and taxes, 2 per cent on $4,000	80.00	
Amortization on A, 4½ per cent, 15 year life	67.50	
" " B, ½ " 50 " "	12.50	
		$400.00
Operating Cost		
Coal, 475 tons @ $3.00	$1,425.00	
Fireman @ $15.00 per week	780.00	
Supplies and repairs	100.00	
		2,305.00
Total cost		$2,705.00

fahr., the same curve to a different scale giving the average boiler horse power required. The coal consumption is based on an evaporation of seven lb. of water per pound of coal (7 kg. of water per kg. of coal) one change of air per hour in the factory and the supplying of radiation losses. During zero weather 90 boiler h.p. will be required. Having determined the size of boiler plant necessary we are ready to take up the cost of heating.

Table I gives the investment necessary, together with the fixed and operating costs of the plant.

Replacement of the plant has been provided for by a sinking fund drawing 5 per cent interest compounded semi-annually, based on a life of the various parts of the plant as given in the table. The time of the fireman has been figured for the entire

year, as steam at high pressure is required the entire year for industrial purposes. It is of interest to note that the cost of coal represents only a little over 50 per cent of the total cost of heating, and that a variation of 25 per cent in the amount of coal burned causes only 13 per cent variation in the total cost.

Having determined the expense which is absolutely necessary in connection with the power requirements, the question asked

TABLE II

COMPLETE POWER PLANT INVESTMENT

Capacity, 100 kw.

Engine, generator, switchboard, wiring (A)	$5,500.00	
Boilers, steam piping, auxiliaries, (B)	5,000.00	
Building, foundations, stack, (C)	5,000.00	
		$15,500.00
Steam heating plant		4,000.00
Additional for power		$11,500.00

FIXED COST OF POWER PLANT

Interest, 6 per cent on $15,500	$930.00	
Profit, 5 per cent on $11,500	575.00	
Insurance and taxes, 2 per cent on $15,500	310.00	
Amortization on (A), 3 per cent (20 year life)	165.00	
" " (B), 4½ " (15 " ")	225.00	
" " (C), ½ " (50 " ")	25.00	
		$2,230.00
Fixed cost on heating plant		400.00
Additional for power		$1,830.00

OPERATING COST OF POWER PLANT

240,000 kw-hr.

Coal @ 7.39 lb., 887 tons @ $3.00	$2,661.00	
Banking, 181 tons @ $3.00	543.00	
Night heating, 202 tons @ $3.00	606.00	
Engineer @ $18.00	936.00	
Fireman @ $15,00	780.00	
Water	100 00	
Oil, waste, supplies	150.00	
Repairs	200.00	
		$5,976.00
Operating cost of heating plant		2,305.00
Additional for power		$3,671.00
Total additional for power		$5,501.00
Cost per kw-hr		$0.0229
Cost per h.p-year		$51.40

is whether it is advisable to go a step further and make the additional investment necessary for generating power, or whether it shall be purchased from a power company. The answer, obviously, depends upon the additional cost of producing this power and the rate at which power can be purchased. Having determined the former, the rate at which power can be purchased to advantage is fixed.

The concern under consideration has a maximum demand for power of 100 kw. (134 h.p.). The average load is 80 kw. (107 h.p.) giving an 80 per cent ten-hour load factor. The engine is a Corliss non-condensing, requiring 30 lb. (13.6 kg.) of steam per indicated horse power-hour. The boiler evaporation is taken at seven lb. of water per pound of coal, (7 kg. of water per kg. of coal) giving a coal consumption of 4.3 lb. (1.95 kg.) per indicated horse power-hour. The efficiency from steam cylinder to switchboard is 78 per cent, giving a coal consumption of 7.39 lb. (325 kg.) per kw-hr. or 5.51 lb. (2.5 kg.) per h.p-hr. at the switchboard. The factory runs 300 days per year.

In Table II is given the investment cost, fixed cost, and operating cost of the plant. Allowance is made for the cost of heating, as calculated above.

Among the items of fixed cost will be found one covering a profit on the additional investment required for a power plant. It is quite clear, I believe, that a concern is not justified in investing in a power plant, unless the capital so invested returns the same profit as if invested in the most profitable part of the business still capable of extension. When the added risk is taken into consideration, I think this could safely be raised to 10 or 15 per cent.

There is nothing, I believe, among the items of operating cost that requires explanation, with the possible exception of the night heating. The engine is only running ten hours per day. It is evident then that, unless live steam is supplied to the heating system during part of the remaining 14 hours, the temperature will fall below that safely allowable. This feature is too often overlooked by the average power user. He thinks that if he installs an engine his heat will cost him nothing, forgetting that every night his watchman is turning live steam into the heating system for a length of time depending upon the temperature outside.

In Fig. 2 an attempt is made to show graphically the relative quantities of coal necessary for power and heat. The area double cross latched represents the saving in coal effected by using the engine exhaust for heating the factory.

It is evident from these results that if power can be purchased for 2.3 cents per kw-hr. there is no advantage in installing a steam power plant. At the present time, however, an engineer would scarcely make any decision without investigating the cost of producing power by means of a gas producer plant. Before

taking up this question, I wish to call your attention to the fact that a 50 per cent increase in the amount of coal required for heating causes only a 9 per cent reduction in the cost of power. I should like, in contrast to this, to show the effect of a variation in the ten-hour load factor.

By load factor I mean the ratio of the average load to the maximum load for a given period of time; in this case ten hours. I wish to mention here that 90 per cent of power users do not know the load factor of their factory. Nearly all of them will tell you that their load is absolutely constant. The point was brought home very forcibly to one manager when a graphic wattmeter was installed and he could see with his own eyes that it took half an hour for the men to get their work started in the morning, that they began to stop working half an hour before

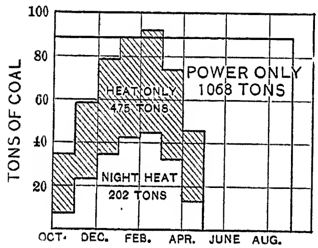


FIG. 2

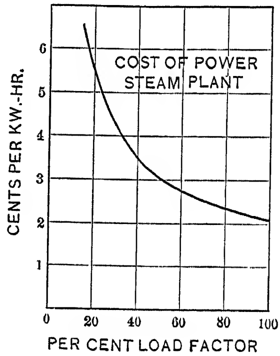


FIG. 3

noon, and that the same performance was repeated in the afternoon in starting and stopping. Under the best conditions it is difficult to get a load factor of 80 per cent, while printing and machine shops only have 40 or 50 per cent.

In the assumed conditions the load factor was taken at 80 per cent. It is seen from Table II that the only items which will be affected by a reduction of the plant output are the first item of coal, and the water. The amount for water is so small as to be negligible. The first item of coal represents roughly 48 per cent of the net cost of power. A decrease in the load factor from 80 per cent to 40 per cent will, therefore, decrease the output 50 per cent and the cost of production 24 per cent, increasing the cost per kilowatt-hour 52 per cent or to $3\frac{1}{2}$ cents per kw-hr. Plotting a curve for different load factors and the corresponding cost, we get the result shown in Fig. 3.

The heating is assumed constant, and this introduces a slight error for load factors under 30 per cent, as the average load on the engine then becomes less than the average heating requirements and necessitates supplying live steam to the heating system during the daytime. The main idea is to show that, while the average manufacturer does not know the load factor on his factory, it is the most important element in his power cost.

The curve will further serve to show the mistake which nearly every manufacturer makes of figuring his power on a horse power-year basis. In the case of the above plant the manufacturer would consider that he had a load of 134 h.p., the maximum demand. As the maximum demand remains constant for all load factors, the cost per horse power-year figured on that basis would be about $41 at 80 per cent load factor and $31 at 40 per cent load factor, a decrease of 25 per cent instead of an increase of 50 per cent. The cost per horse power-year based on the average load is $51, as given in Table II, for 80 per cent load factor and $78 at 40 per cent load factor. In this latter case the actual cost per unit is over 2.5 times that figured by the manufacturer.

It is interesting to note the effect of the use of exhaust steam on the cost of power.

If all the exhaust steam from this plant were necessary for industrial purposes, the only additional investment necessary to produce power is the $5,500 for an engine and generator. The fixed cost on this amounts to 16 per cent or $880 per year. The extra operating cost is an engineer at $936 and $250 to cover oil, waste and repairs, giving a total of $2,066 for generating 240,000 kw-hr., giving a net cost of 0.86 cents per kw-hr. It is quite evident from this that the amount of low-pressure steam that can be utilized plays a very important part in the cost of power.

Gas Producers

The most active competitor of the steam engine for power production is the gas producer plant. This type of plant, which has developed since 1900, has shown remarkable economy of coal consumption when handled by experienced operators. The United States Geological Survey Report on Gas Producer Plants shows that for an average of a great many tests the non-condensing steam plant requires 2.7 times as much coal per unit as the producer plant. Their results give a thermal efficiency at the switchboard of 4.86 per cent for the steam plant and 13.5

per cent for the producer plant. The maximum attainable efficiency is probably 10.3 per cent for the steam plant and 21.5 per cent for the gas producer under present conditions. In view of this known economy a great many producer plants have been installed in the last few years.

For the factory under consideration the conditions will require the installation of a 175-h.p. engine and producer, and in addition a heating plant for heating the building. As this heating plant is required in any event, the cost of heating is eliminated as a comparative factor in the problem. The investment, fixed costs, and operating costs of this plant are given in Table III. The cost of the plant is somewhat higher than the corresponding steam plant. The life of the plant is also shorter. This gives a higher fixed cost than for the steam plant.

TABLE III

GAS PRODUCER PLANT

Investment		
Engine and producer (A)	$11,900.00	
Generator, switchboard, wiring, (B)	2,500.00	
Building, (C)	2,500.00	
	$16,900.00	
Fixed Cost		
Interest, 6 per cent on $16,900	$1,014.00	
Profit, 5 per cent on $16,900	845.00	
Insurance and taxes, 2 per cent on $16,900	338.00	
Amortization on A, 15 year life, 4½ per cent	535.00	
" " B, 20 " " 3 "	75.00	
" " C, 50 " " ½ "	12.50	
		$2,819.50
Operating Cost 240,000 kw-hr.		
Coal, 3 lb. per kw-hr. @ $4.00, 360 tons	$1,440.00	
Engineer @ $18.00	936.00	
Oil and waste	125.00	
Repairs	300.00	
Water	133.00	
Emergency service	300.00	
		$3,234.00
Total		$6,053.50
Cost per kw hr	$0.025	
Cost per h.p-yr	$56.20	

The operating costs of the producer plant are only about one-half that of the steam plant. This, however, is counterbalanced by the cost of heating. The final result gives a slightly higher cost for the gas producer plant. The ratio of the fixed cost to operating cost in the two cases, however, produces a very marked effect where the load factor is poor. The only items effected by the output of the plant are coal and water. These represent

only about 27 per cent of the total cost, as against 50 per cent with the steam plant, the result being a very much higher cost for the gas producer at low load factors. The poor fuel economy on light loads would further exaggerate this effect. . Fig. gives the cost at different load factors.

The dotted lines are a reproduction of the steam plant costs given in Fig. 3.

It is quite evident that where the use of exhaust steam amounts to anything, a steam plant can show greater economy than a gas producer plant. For a 24-hour load with only a small demand for steam to heat the building, the gas producer is the most economical.

I believe that the cost of power, as worked out in the two cases just given, represents a condition which will be found most often. Twenty-four hour services and condensing plants are the exception and not the rule among the factories under discussion, and it would not be worth while to lengthen this paper by including them.

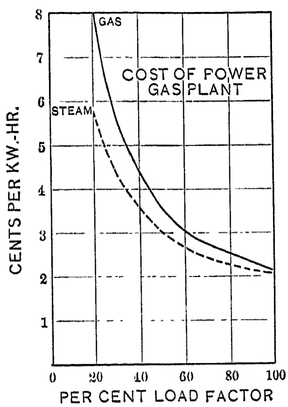


FIG. 4

I am very strongly of the opinion that manufacturers lose perspective in judging of the importance of the cost of power in comparison with other factors in their cost of production. It is rarely that the power cost represents more than 2 per cent of the cost of the manufactured article. A saving as large as 25 per cent in the cost of power then only reduces the total cost ½ per cent. Balance this against the item of labor which often represents 50 per cent of the cost of production. A saving of one per cent in this factor accomplishes the same result as a 25 per cent reduction in the cost of power. It seems to me that the chances of a one per cent reduction in labor cost is greater than a 25 per cent saving in power cost, when it is considered that a manufacturer is quite expert in labor matters and inexpert in power conditions.

Recently I read an article on the effect of factory ventilation on improving the efficiency of workmen, and it appeared that an increase of 25 per cent in the factory output was possible under certain conditions, if a proper ventilating system was installed.

Compare the relative importance of this saving with a few hundred dollars possible in the case of the same money invested in a power plant.

The time is rapidly coming when the small power user will take all these economic and technical questions to a consulting industrial engineer for solution, just as he takes his legal questions to a lawyer. The large manufacturing companies are already doing so; and in a few years the purchasing of power plants by factory owners, without any consulting engineering advice, will be a thing of the past.

Discussion on "The Cost of Industrial Power", Toronto, January 13, 1911.

A. M. Dudley: It is common information among the men who are doing industrial engineering, that factory power users have the most diverse methods of figuring the cost of their power, and that very often their ultimate conclusions are as erroneous as in the case of the user mentioned, who honestly believed that his power was costing him $15 per h.p.-yr., where, as a matter of fact, it was really costing five times as much. This error, as pointed out, arises not so much from error in figuring the cost of all the power used in the aggregate, as in an error as to what is the actual amount of power required and used. One great element in causing this error is that of load factor, and as Mr. Hibner points out, it is also one of the largest factors in determining the actual cost of the power. Load factor is defined in this paper as the relation of the average to the maximum load. This at once suggests two things; first, that a plant load factor is made up to a considerable extent of the load factor on the individual machines. As it is a fact that all machines run most efficiently at or somewhere near their full load rating, a plant having a load factor of 50 per cent, which is made up of half the machines running under full load all the time, may have a cost of power per kilowatt-hour less than another plant having the same 50 per cent load factor but made up of all the machines running half loaded all the time. This is one urgent reason why careful tests on individual machines should be run to see whether units of the proper capacity have been selected for the various applications. The writer has in mind a plant driven by induction motors where the plant power factor was brought up from 35 per cent to 65 per cent simply by shifting the motors from one tool to another more nearly fitting its capacity, and the purchase of one or two new units of the smallest size at the bottom of the line. This not only directly reduced the operating cost by running the motors at their most economical load but had it been properly anticipated on the original installation, would have permitted the use of a smaller generator with consequently reduced investment charges.

The second suggestion in regard to the question of load factors is that users are apt, in figuring their power consumption, to take the capacity from the name plate of the driving motor or motors and consider that as the average consumption. If, as is more often the case than not, this unit has been liberally allowed for, the ultimate calculated consumption of power is in error by even more than the ratio of the maximum to the average consumed. When these facts are considered, it is not so hard to understand why the cost of power is sometimes figured in error by 400 per cent. As an illustration of how serious this error may be, figures are submitted showing the ratio of the *average load* to the *connected load*, which are the result of a number of

observations and fairly represent the average condition. These figures are as follows:

Cement mills, 85 per cent.
Textile mills—cotton and woolen, 75 per cent to 90 per cent.
Tanneries, 55 per cent.
Ice machines and refrigerating plants, 53 per cent.
Marble works, 51 per cent.
Flour mills, 50 per cent.
Carriage and wagon works, 35 per cent.
Machine shops, 35 per cent.
Breweries, 33 per cent.
Boiler shops, 28 per cent.
Sheet metal manufacturing, 27 per cent.
Soap manufacturing, 28 per cent.
Rubber manufacturing, 25 per cent.
Wood working, 10 per cent to 35 per cent.
General average of all industries, about $33\frac{1}{3}$ per cent.

Another point which the paper brings out and which merits recognition is the utility of the graphic meter in récording not only the actual power consumption in laying bare errors of this nature, but its secondary use of indicating interesting and pertinent facts regarding the management of individual machines and the conduct of the entire factory. For all these reasons, tests based upon graphic meter charts are most valuable in settling the much mooted question of power costs.

One of the most valuable deductions is that the cost of power must be kept in its proper perspective with regard to the total cost of production in an industrial plant and that after all, it amounts in general to perhaps the astonishingly low figure of 2 per cent. This is probably the real reason why we have not in the past had more investigation of this subject, but it must be accepted with modifications, and one of the chief of these is that while the cost of power in industrial plants is a small proportion of total cost, the cost of interruptions to the power may cause serious disaster. From this, we may draw two conclusions; first, that continuity and reliability of service must have their due consideration in balancing the central station supply against the private plant and, second, whatever makes for reliability and continuity of service, even at some sacrifice of economy in detail, may be installed and will ultimately prove the greater economy through insurance of uninterrupted output. This brings the conclusion that Mr. Hibner had perhaps better split up his generating units and put in some reserve capacity. When the necessary investment charge is added to take care of this I believe, the paper will cover all the elements that go into the problem and furnish in addition, valuable data on the solution of a specific case.

E. Richards: There is one matter that I wish to briefly comment upon before calling on some of the other members to take part in the discussion. I have no thought of criticising Mr. Hibner's

paper. I think that his values have been carefully chosen. I had occasion to check up some of them and I think that the average represents very good, typical, modern practice. I am, however, interested, and somewhat amused, from one standpoint, in the view that is taken of the typical basis of power cost. The central station man makes the cost of the unit of power the basis for comparison, and he gets into the way of thinking only in kilowatt-hours. Now it is not at all apparent to one who has studied the power question from a general standpoint why this should be so prominent. Such is not the basis of cost of power in any case. The cost of power is not based on the kilowatt-hour; it is not the central station man's basis of cost but it is his method of selling, and the time may come and I believe is coming when we will break away more or less from this basis of comparison of power cost. As transmitted power becomes more prominent in power problems with its accompanying high fixed charges, the kilowatt-hour will become somewhat relatively less important. The kilowatt-hour may figure for convenience in cases where the actual power consumed by any user does not figure in the maximum demand coming upon the generating apparatus of the plant or station, but apart from that it is only a convenience in the selling and measuring of power. But in cases of transmission the much higher factor in the power cost is the demand that it brings upon the plant because of the relatively large fixed charges.

Ivar Lundgaard: There are a great many factors in power generation of which we do not possess sufficient statistics to judge rightly, and it is only by the action of such bodies as the Institute that we can obtain such data. Mr. Hibner's paper has been very clear in defining the various factors and really does not leave much to be said when it is limited only to the cost. What I am going to say in the following has a bearing on the so-called fixed costs.

One of the most notable facts about power generation is that improvements have been made at a steadily increasing rate. The last ten years have seen more real improvements in power generation than any previous period of the same length, and some that have been made in the last couple of years assure me that the progress is not going to be retarded. I think we will see still greater developments in the future than we have seen in the past. I cannot go into the subject of improvements very largely but I can mention a few.

There have been enormous advances made in the art of long distance transmission, the size and efficiency of steam turbines have grown, the oil engine and also the gas engine have been developed in the last ten years. Power plants have been improved in arrangement with resulting economy of space and labor, and, on the whole, it has resulted in materially reducing the cost of power. It is also worth noticing that the central station has always been the first to take advantage of

any real advance that has been made in power generation. The manufacturer cannot readily follow the times because he has 98 per cent of other things to do, and when he has his money tied up in a plant, that plant will go on producing power at the given cost until its natural departure to the scrap-heap, unless it has an earlier death as has been so often the case recently. In such a case, of course, the value of the plant is lost. There have been a great number of such early deaths of private plants in recent years, and that should cause serious consideration. Another thing that adds to the importance of this, is the fact that the private plant dies hard. There are many reasons for this. No factory can tell to-day what its business is going to amount to in five years from now. Its business may increase or it may decrease, and one thing is sure, that a factory cannot stop growing because its power plant is too small. It has to keep on adding units to the power plant. While that may be all right, it usually results in a very undesirable type of plant. The multiplication of units means more attention, more repairs, more labor, lower efficiency and so on. Now, suppose that a factory with a plant of its own is placed in a position where it might possibly buy power from outside sources at a cheaper rate than it manufactures power itself. You see where the fixed costs hold them. They cannot take advantage of cheaper power unless their plants happen to be in extremely bad shape. Suppose a manufacturer starts in business at a time when a great development has been made in power, and installs a plant very much superior to that of his older competitor. The first plant will find itself at a disadvantage in the competition because it has a plant that costs so much more to run. Suppose a factory goes out of business or wishes to move the power plant. In both cases it represents only so much expense or loss in moving or in having to be sold. Suppose a conflagration destroys part of the factory. It does not matter whether this part is the power plant or the factory itself. The business is going to suffer a loss, because the business loss cannot be compensated for by insurance. No insurance company will compensate for stoppage of business on account of a boiler explosion. It only reimburses you for the cost of the buildings or a few large losses, perhaps, but not for stoppage of business. I am well aware that there are risks in all businesses, but it is worth while considering if it is not better from an investor's point of view, to avoid investments in a power plant that will not yield a substantial profit when compared with the cost at which power can be purchased. Any conservative business man will hesitate before spending a large sum of money on a proposition that is so uncertain from a profit-seeker's point of view. There is one argument frequently brought into the discussion, and that is, the manufacturer wishes to be independent. It is safe to say that the same manufacturer is tied hand and foot when he has his money invested in a private plant. As long as he uses the central station power he is free to

decrease or increase his business without suffering from the consequences of excessively heavy investment charges, or he can discontinue his business or do anything he likes, and he will be much less likely to have interruptions on account of strikes and labor difficulties.

Mr. Hibner brought out the fact that it is important for a man in the manufacturing line to devote his time to his business. I believe there is an old adage about that. You may ask what all this has got to do with the cost of power. Mr. Hibner has shown that the fixed costs amount to about 50 per cent and that the fixed cost largely depends upon the amortization, which again depends upon the life of the plant. Now the life of the plant is usually considered to be the length of time that the engine can possibly keep on turning the flywheel, but I believe I am justified in objecting at this point, because we should not consider the possible life of a plant but the useful life of a plant. I have been trying to obtain statistics as to the useful life of a plant, and I have been looking for them far and wide. I know that some plants go on living after they should have been retired and put on the pension list; I know that some plants have been giving useful service all their lives, and I know that some plants should never have been built.

Now the question of useful life is of such importance I wish to call attention to it and emphasize the necessity of collecting such information that will put us on a firm basis as to where we stand on this item.

I see one objection to one of the figures in the tables. The building is put down at $2500; the fixed cost is $1\frac{1}{2}$ per cent. The plant is given a twenty year life. Now when that plant is out of business the probability is that the building itself will be useless. Therefore I think it is a good practice to figure the depreciation on the building, the same as that of the plant. I think that our common sense and observation tell us that when the plant has ended its useful life the building does not fit the new condition that will surround the new plant.

A. S. L. Barnes: There is one point I wish to speak of and that is the cost of obtaining power from a generating station against that of generating it on the premises, and transmitting it either electrically or mechanically. In the former case the manufacturer does not have to pay for any power he does not use nor for the standby losses at noon and other periods of stoppage which in the case of some plants is pretty heavy. In the case of obtaining power from an outside source the manufacturer saves all that and the cost of keeping the boiler and the steam pipe hot. If the steam pipe mains are of any considerable length, it is usually a considerable item of the total cost of the coal, and personally I think a certain amount for coal ought to be put down for fixed costs for whether you are using any power out of the coal or not you have to pay for it. In the case of a generating station if you imagine the necessary engines running

but not supplying any power, in most cases I think it would be found that the coal used under these conditions, without turning out a single unit, would be a very fair percentage of the total cost used under ordinary conditions. I had an opportunity of testing that to some extent some years ago, and it worked out to be about 6 per cent, and as coal in that instance was 50 per cent of the total expenses of running the station the fixed charge for coal was pretty considerable for the twelve months.

A. E. Hibner: There are one or two points brought up in Mr. Dudley's discussion I would like to speak of. He emphasized the importance of having the motors which are of the right size for the work to be done and showed how the power factor can be increased, and had been increased in several cases by doing this. Increasing the power factor, of course, increases directly the capacity of the generator. Thus, obtaining a higher power factor would mean a smaller generator than would otherwise be necessary. The motor cost itself of course would be decreased, the smaller motors costing less. The efficiency of motors as Mr. Dudley points out are best when running at their full load. This does not mean, however, that a 15-h.p. motor running on a 7-h.p. load would not be running as economically as a 7-h.p. motor at full load. In fact the efficiency that is obtained by a 15-h.p. motor running at half load is as good as a 7-h.p. motor at full load. The main thing is to have the motor small enough so as not to have a lot of money tied up unnecessarily.

Mr. Richards brought up the point of charging on the basis of the kilowatt-hour. Most all power companies are now getting round to a system whereby they charge a fixed amount plus kilowatt-hour rate; that is, a fixed amount which would be compared with the fixed cost on the steam plant, plus a kilowatt-hour operating charge. In fact, some companies are coming to a three rate system. A fixed sum, say, of $30 a year which covers the cost of reading the meter and so forth, in other words a sum which is in proportion to the number of consumers on the line whether they use the power or not; then a charge of so much per horse power of maximum demand, then a kilowatt-hour charge.

Mr. Lundgaard has brought out the point that considering the risk involved the item of profit of 5 per cent can very well be increased to possibly 10 or 15 per cent.

A. L. Mudge: In any discussion on the cost of industrial power we should strongly emphasize the distinct advantages obtained by distributing and applying power electrically as against transmitting it by shafting, belts and other mechanical means. Mr. Hibner states that the cost of power in many cases is not more than 2 per cent of the cost of the final product. Even if we forget all about the relative cost of producing power by different means, the arguments in favor of electric drive in factories would be just about as strong. The following are some of the advantages which result:

First, the machines can be located in such a way as to best

facilitate production, for it is not necessary to locate a machine so as to line up with a certain countershaft.

Second, where heavy work is done, every machine can be served by an overhead travelling crane, as there are no countershafts, belts etc., to interfere.

Third, where a change of speed in machines is of value, for example, on lathes, boring mills, etc., such speed variation is readily obtainable to a very fine degree and inside of wide limits, and this without stopping the work for an instant.

Fourth, on account of doing away with belts, shafting and hangers the lighting is greatly improved, greater cleanliness and safety are obtained.

Fifth, on large work portable tools can be freely used, thus the tools can be taken to the work instead of the work to the tools.

Sixth, certain departments or single tools in the factory can be run at night without having to run the main engine and most of the shafting. This applies more particularly to the case of power obtained from a central station when it is only necessary to close a switch to start the motor instead of bringing in the fireman and engineer in order to furnish power for the work of perhaps two or three men.

Advantages such as the above may give economies which will decrease labor cost or increase rate of production in such a way as to save the total cost of power several times over, and the way we should look at this question is that the immense advantage in electrical drive in factories is not merely in decreasing the power cost, but in the increased efficiency both of men and machines, due to the great flexibility of the electric drive and the improved conditions generally which it creates.

Discussion on "Comments on Fixed Costs in Industrial Power Plants", and "The Cost of Industrial Power", New York, March 10, 1911.

Percival Robert Moses: The paper presented by Mr. Parker purports to be a discussion of the cost of power generation and certain features in connection therewith in small plants of the industrial type. Such plants are usually understood to mean manufacturing establishments, but the tabular data presented apply to department stores and have nothing whatever to do with industrial plants as usually understood. I shall discuss this tabular data later.

Taking up the paper in detail, reference is first made to the marginal principle. This principle, as I understand it, is the principle enunciated by Wellington in his theory of street railway location, *i.e.*, that no expenditure is justifiable unless in itself it will earn a fair return. The author states in the following paragraph that since the installation of a plant, costing $10,000 to $20,000, would constitute a physical improvement to the property, it is obvious that the tax assessment will be increased thereby. Practical experience points the other way. I have never had the taxes increased on any building or manufacturing establishment because of the installation of a small private plant; nor, on the other hand, do I know of any decrease in taxation resulting from the shutting down of such a plant.

Regarding insurance, he also discusses the question of insurance and, later on, allows 3 per cent for taxes and insurance. I have already discussed the question of taxation, and the question of insurance is usually one of small moment. The rate in modern fire-proof buildings rarely exceeds one-quarter of one per cent on 80 per cent of the actual value. This is for fire insurance. If to this be added the liability insurance, the total additional insurance due to the operation of a private plant will, even theoretically, not exceed one per cent of the cost of the plant. I say "even theoretically", because unless a plant is quite large, *i.e.*, around $30,000 or $40,000 in value—the amount of insurance on the building is rarely changed. As for the liability insurance, it will usually be found that the labor increase in an industrial plant, due to the installation of a small private generating plant, is inconsiderable and, as the liability premium is figured as a percentage of the pay roll, the *addition* to the liability insurance premium which is the only part that should be charged to power generation is usually nominal. Of course, the matter should be considered, but it should be considered practically and the actual cost allowed not an imaginary cost.

This expense for liability and fire insurance, the author states, is existing whether such insurance is actually carried or not. The fact is lost sight of that the presence of an electric plant, with its additional employees, is an additional safeguard against

fire, and if we begin to allow for theoretical additions to insurance we should also allow for theoretical increase in efficiency of fire protection.

The author's discussion of the depreciation of a plant seems entirely fair, except that I believe that in an industrial plant, where the plant is liable to increase in size or to change its character, the depreciation rate should cover the possible obsolescence of the machinery. This is a matter which must be determined in each case by the possibilities of the case.

The author's discussion of the supervision of a plant does not seem to me to be well based. He discusses the possible proportion of the time of a manager which may be taken up in connection with the power plant, then allows for the possible value of this man to the concern and the possible profit that might be obtained from the use of this man's whole time if he were not distracted by the power plant. He forgets to allow for the increased efficiency of the manager due to his increased knowledge of power generation, and that the manager through his connection with the operation of a power plant may learn something that may enable him to double the output of his business. I am treating the matter sarcastically because if we go into possibilities, or, as they were called in the Alabama Arbitration, indirect claims, we will never get at the facts. I believe that it is proper to charge against the plant operation the actual cost of such time as is required for supervision *of the power plant required for the generation of electricity*; *i.e.*, the additional time of the manager that is required to supervise the operation of the electric generating plant—not the time required for supervising the operation of the boilers or deciding questions in connection with the power transmission or with the motors or with the air compressors, but solely the time required in connection with the electric generating plant. If this time is analyzed, it will be found to amount to a few hours during a year—not a few hours a week. And even this amount of time is partly balanced by the services rendered by the operators of the electric generating plant in other parts of the works.

After allowing for interest on the investment and depreciation and possible obsolescence, and taxes and insurance which do not exist in most cases, and for a very large proportion of the time of the superintendent at $10,000 a year the author of the paper proceeds to add a fair profit based on the average profit in the store.

If this paper were an argument in favor of central station service and not an unbiassed investigation of the cost of industrial power, such a proposal might be understood. On the same theory, the rent of the building should be charged at the average profit obtained by selling merchandise—not at what the money could be borrowed for. And, in fact, the merchant could figure that he had no profit at all, because if he had to pay the averaged profit ratio as interest on all the money he borrowed from the

bank, there would be no profit. On the author's theory, the fore, we would have clearly proved that the manufacturer business man had no business to be in business at all.

The recognized and standard method is to charge intere on the investment at the rate at which money could be borrowe and this interest on the cost of the electric plant is just the sa as the interest on the cost of a building or the interest on t cost of an elevator machine; it is part of the rental paid and h nothing whatever to do with the ratio of profit on the sale merchandise.

The next item in the discussion is the building space and re estate. This is a matter that must be considered in each ca In some cases it is true that the space taken up by the electi plant is valuable and a fair rental value must be assessed agair this space. In fact, it may be stated that in all large plar this is the case. But in small plants, of which the paper treat the reverse is true; and it is the exception rather than the ru that the space taken up by the private plant is space which ma be used for other purposes. It is usually space required becau of allowance for other machinery, and because of the objectic on the part of the builder to place himself entirely in the hands an outside company.

Appendix A is an interesting discussion of the margin principle, but like most general discussions its application special cases requires careful consideration, and Appendix is a mathematical discussion of amortization or depreciatio as it is usually called. It is interesting to note that the auth uses six per cent in this mathematical discussion, whereas on th fair profit theory it would seem more correct to allow the averag ratio of profit.

Appendix B, which is the part of the paper that would mo appeal to the ordinary business man, contains tabulated stat ments of figures "presented to and endorsed by the owne and manager of a large mercantile establishment." The figure may have been endorsed by a business man, but they are ce tainly not correct insofar as standard practice is concernec The plant consists of a 100- and a 50-kw. unit. The cost of th engines, dynamos and switchboard is placed as approximatel $9,000. The engines are high-speed engines. The actual cos of a 100- and a 50-kw. unit, delivered and erected on founda tions ready for steam and electric connections, could not excee $6,000 and I have recently purchased similar equipments fo $5,500, as compared with approximately $9,000 given by th author. Similarly, boilers for 150-kw. units should not cos $6,200. Of course, if boilers were to be installed to take car of every thing else in the building besides the electric equipmen they might, but the cost assignable to the power plant is cer tainly not correctly stated at $6,200.

The total given by the author is $20,265 for a 100 and 50-kw. machine erected and connected, with the necessary boiler

and stack. I presume that this is all in addition to the heating equipment cost and boilers required for other purposes. This is at least 50 per cent too high a cost. Not over two weeks ago, orders were placed for two 100-kw. direct connected, high-speed engines, with the necessary additional boiler capacity required for their operation, smoke breeching, steam fitting, wiring, switchboard, at a total cost of $13,000 including engineering charge.

Table 2 shows marginal interest 6 per cent, amortization 2.63 per cent, taxes and insurance 3 per cent, and fair profit ratio (this is in addition to interest) 11.5 per cent, or a total of 23.13 per cent. In my opinion if we allow 6 per cent interest, depreciation 2.63 per cent or even 5 per cent would be more safe, and taxes and insurance 1 per cent we have a total of 12 per cent on a correct installation cost of not over $12,000, or $1,440 per year for fixed charges, as compared with over $4,441 allowed by the author.

I have gone into details in this matter, as this shows how a little added to this item and a little added to that item, and a percentage charged here and a percentage charged there, each so small in itself, may entirely change the facts.

The same thing is true of the gas engine plant next cited, a small plant of 120 h.p., using producer gas produced from 4.5 lb. of coal per kw. hr. Our records from several such plants, operating under poor conditions, show less than 2.5 lb. of coal per kw. hr. A plant recently installed at Stanley G. Flagg & Company's works, Pottstown, Pennsylvania, a 175-kw. plant, ran for a month under regular working conditions with no allowance extra for banking; *i.e.*, the actual coal used for all purposes, was 2.05 lb. per kw. hr., less than one-half that allowed by the author, and this was No. 1 buckwheat coal.

The amount of coal and the cost of labor allowed seem about correct in Table 3, except I do not see why it is necessary to have a night engineer all the year around, whereas when the plant is only used for heating the fireman is only kept at night for 20 weeks. It is evidently not for generating electricity, because an allowance is made for emergency service.

The main discrepancies come under the head of Fixed Charge, which is estimated at $4,441, whereas correctly, as has been stated, this should not exceed $1,440, a difference of $3,000. $1,000 a year is allowed for the manager's time at $12,000 a year rate, it being assumed that the manager will lose this amount of time in connection with the power plant, which he would otherwise use, and that this time will be solely devoted to the electric generating end of the plant as distinct from the rest of the heating plant and power plant.

The space value is stated at $1.00 per sq. ft. This is space—not boiler space—in addition to that required for boilers and other machinery in the basement. The usual rate for basement space is from 10 cts. to 25 cts. per sq. ft. and, in some rare cases,

40c. per sq. ft., particularly for space in the middle of a store basement.

Altogether, there seems to be about $4,200 charged against the plant operation which should not be so charged, making the actual cost of the power plant operation $8,763 as compared to over $10,000 with the central station service. It should be noted that the table only allows $25.00 a year for the manager's time, including clerical expense, with the central station service, whereas $1,150 is allowed with the private plant, and the only addition in the machinery line has been the self-oiling engines and dynamos and their connections.

In the gas engine plant, Table 4, 25 per cent is charged for fixed charges, as compared to 12 per cent. The coal per kw. hr. is stated at 4.6 lb., whereas the usual ratio for producer gas engines is a little over 2.25 lb., and this includes coal used for banking. No provision is evidently made for re-circulation of the water, and the allowance 27.2 gal. per kw. hr., is greatly excessive.

One thousand dollars a year is allowed for this little bit of a plant for manager's services. An engineer is charged for extra, presumably in addition to the man operating the heating plant. For a plant of this size, one man should be able to do both, and usually does.

Altogether, the figures presented do not seem to represent even fair average practice, and the allowances for fixed charges and manager's time cannot, in my opinion be defended upon any reasonable ground.

In general the paper is an argument for central station service, and is not an investigation of the cost of industrial power.

David B. Rushmore: Industrial plants are rather sharply divided into separate classes. In the large cities one finds many small industrial plants of a few hundred horse power each, some directly connected to a central station. There also exist other plants of this nature which demand many thousands of horse power, where the desirability of connection to a central station is not so apparent. The cost of industrial power is measured by the manufacturer not at the switchboard but at the point of utilization. In manufactured articles there is a wide variation as to the ratio which the cost of the power bears to the cost of the finished product. In many cases this ratio is not large, which points out the fact that frequently the correct application of the power is of more importance than the cost of it. By the proper design of the power plant, of the electrical system to be used, of the particular motors and controllers, etc., the product in quantity and quality can often be favorably affected to a very considerable degree.

The cost of power is made up of many items, of which the fuel cost is but one and sometimes a minor one. The interest charges, the cost of operation and the maintenance and repair items in many cases, even where a blast furnace or coke oven gas is used, make it preferable to use steam turbines instead of gas engines.

Electrical power derived from transmission systems, connected to hydroelectric stations, is being more and more used for industrial power purposes. Continuity of operation is a factor of prime importance in manufacturing establishments, and the reliability of these systems is a consideration of the first magnitude. Transmission systems are in operation which have practically no interruptions, although there are, of course, exceptions. In connection with power taken from transmission systems, the use of a steam turbine reserve, which can be thrown on the distributing system quickly, is in some cases necessary and in many cases desirable. It is not in general appreciated how quickly steam turbines may be started, synchronized and loaded. The time from the first indication of trouble on the transmission line to the condition where the turbo generators are fully loaded on the system need not be over 30 sec., starting all the machines and auxiliaries from rest. The condition of interrupted power supply is being rapidly removed.

R. P. Bolton: I think we are all under a considerable debt of gratitude, whether interested in one form of the use of power or the other, to the authors of these papers. They have some sound and fundamental facts and so far as my judgment and experience goes they are right in their general conclusions. I must controvert the statements of a previous speaker in so far as they refer to insurance on labor, on the hazardous class of which rates have now risen until they amount to nearly six per cent, in addition, to fire and boiler insurance, which thus form a not inconsiderable item of expenditure.

The question of depreciation is very often misunderstood. Depreciation is the result of the failure of maintenance, of upkeep, of repairs, and of all the other attentions that are given to machinery to effect their full purpose of prolonging its useful and economic existence. There are two kinds of depreciation, that which comes about from what is commonly known as physical decay or obsolescence, and that which is due to economic causes. I congratulate myself that my mind has been in this matter working along the same lines as Mr. Parker's, although we have been separated by the length of the State of New York from each other.

As regards the provision for depreciation, I find in Mr. Parker's paper that he has amortized depreciation at a rate of compound interest of six per cent. A preceding speaker took exception to the rate of six per cent interest upon the money invested in a plant of machinery but he did not take exception to the use of a six per cent rate on the amortization, because that had the effect of reducing the amount required for depreciation. In the table, the rate of amortization capitalized at three per cent, which is the rate you can get in most savings banks should average $4\frac{1}{2}$ per cent on the total, and therefore the total in Table 2 should be increased about two per cent.

In Mr. Hibner's paper the load factor which has been as-

sumed seems to be too high. In Table 2 on the basis of a working period of 2280 hours per year, it is 86 per cent. By Fig. 3, the actual factor is nearer 40 per cent and the cost would therefore be at least 3.5 cents per kw. hr. This reference leads to consideration of the manner in which uninformed people plunge into the establishment of power plants without knowing anything at all about the subject of load factors. In a recent case where a factory was running on a public service having a very light load and a considerable variation in the power load due to the use of elevators, the owner insisted on putting in a power plant which is so proportioned as to operate on a sixteen per cent load factor.

The use of exhausted steam, as a by-product from plants in commercial buildings, is subject to climatic conditions—the nearer you get to the North Pole the more use may be made of exhaust steam as a by-product; the nearer you are to the Equator, the less use can be made of it. Under such conditions electric demand and heat requirement do not fit together.

The percentages of the sales of live steam supplied by a public steam supply company in this city during the heating months are as follows. October, 3.2; November 7.2; December 15.5; January 25.7; February 22.6; March 20.6; April 5.2. The percentage of steam generated during the same months by a generating plant in a business building near the steam plant is as follows: October 13.4; November 12.9; December 14.8; January 15.0; February 13.9; March 16.1; April 13.73. There are other limitations of the availability and use of exhaust steam, and one which affects the question more than anything else is the load factor. In the operation of a certain generating plant in this city, I found that a kw-hr. is generated for about 6.5 lb. of coal per kw-hr. under the best conditions only for a very limited period of the day. On Sunday the consumption rises to 36 lb. of coal per kw-hr. The generators in that plant are never loaded in excess of 75 per cent of their capacity. Many operating engineers appear to be afraid to operate a unit at full capacity. I recently saw a fine 4-valve engine driving a 250 kw. unit, in a first-class hotel, the load of which at the time was approximately 90 per cent of full capacity, and as soon as that load was reached another generator of equal size was put in operation, reducing the load factor to 45 per cent. I am not against the installation of power plants where they are required, but I am against the introduction of power plants where they are not necessary, and where they are not properly and economically needed is often the place in which they are installed. The kind of engineering I hope to see developed will be that which will refuse to be tied to either side of this question, but will be willing to see the economic side of this very important matter.

Arthur Williams: It seems to me this is a question simply of kw.-hr. cost, so far as the electrical service is concerned, and of the cheapest method of obtaining it. In regard to the first two

papers, bearing upon the cost of operating private plants, I am compelled to take issue with the distinguished authors—they have not placed the cost of current, at least under conditions existing in such a city as New York, at anywhere near its true value. In Mr. Hibner's paper, Table I, we have the cost of steam, and, while the details upon which my conclusions are based will be given in my notes to be published in the PROCEEDINGS, I will say that the amount allowed for heating the building with an average heating load of 62 h.p. is altogether too high. By a process of elimination—first, the correction of the investment, lowering it to $2,000, instead of $4,000, we get nearer to the facts. On this basis the annual " fixed charge " on an investment of $4,000 should be $600, but upon the more nearly correct investment estimate of $2,000 it is only $300. As to coal for heating alone the cost appears overstated. Four hundred tons (for an average of 62 boiler h.p. for the heating season) would be sufficient, which at $3.00 would cost $1200. And in the matter of labor, a fireman's wages for a full year have been charged; assuming, as here, that one would be sufficient, his wages for 30 instead of 52 weeks would be $450. Making these changes, the yearly cost of heating the building in question is about $2,000 instead of $2,705. The point may be small, the saving of $705, but it is referred to later when the cost of operating the private plant is considered. Following the same table, we find, first, rather too small an allowance. Mr. Martin admirably covered that subject. My own criticism summarized fixed charges at 15 per cent, and, making this allowance, the final result, which is shown in detail in my own comments, becomes 5.5 cents per kw-hr., instead of 2.29 cents; that is to say, under the conditions existing in New York, and using the same basis that the author used in his paper, we get the larger average cost.

In table III, we come to the question of the producer gas plant. Apparently the author uses a single unit, compounding the interest on the investment, but at a very low rate, altogether too low for that purpose. He allows simply a single engine for a very important building evidently forgetting that producer gas plants are hardly more reliable in their operation and hardly longer in life than an automobile engine, instead of a steam engine. I have changed the ratio of depreciation on the total investment to 20 per cent, giving the reasons, and in this case we again reach a total cost of 5 cents a kw-hr., instead of about 2.5 cents.

Referring to Mr. Parker's paper he again, estimates 2.63 per cent as the annual depreciation, but I do not know of any case—and I have asked several engineers if they knew of any case—where annual depreciation is actually put aside in a fund upon which interest is accumulated from year to year, and the universal answer is " No." Therefore, in my own criticism, I have taken a general depreciation rate of 7.5 per cent. Mr.

Bolton has given two causes for depreciation, obsolescence and physical life. There is a third, and that is, the moment that a competing service becomes available at a cost not exceeding the cost of operating the private plant, then the depreciation of that plant has become complete, 100 per cent, and so long, therefore, as its operation is continued, it must be apparent that operation is continued at a loss to the operator. I think, therefore, that I have not gone beyond the bounds of conservatism in taking 7.5 per cent throughout my notes, as the basis of depreciation. Finally, in going through Table I of Mr. Parker's paper—I trust he will pardon me for criticising it in detail—we find that the total cost becomes, by a process of elimination, $8,000 for operating the plant, which is 7 cents a kw-hr.

I heartily accord in Mr. Bolton's suggestion, and I am seriously of the opinion that it is a matter of very great importance to this Institute, that we should have consulting engineers who have no interest whatsoever in the outcome of their advice; that they should be called in to advise the owner as to the cost of power, taking everything into consideration, without reference, finally, to the outcome. Under the present system very largely the engineer must prepare plans and specifications, which are absolutely necessary in most cases to determine the cost and the best way of obtaining power, and if the plant is not installed, that entire expenditure of time and money is lost to the engineer. I think that this, at least in this City, is a very general practice, and in my opinion it is a wrong practice and should be changed. I have ventured to offer some suggestions on this point, which will appear in the PROCEEDINGS.

Finally in summarizing what charges should be allowed, I have taken six per cent as the allowable rate on money, on the theory, at least, that that is as little as any one would expect to get on his investment for any investment corresponding to a private plant.

Now, a word about operating costs. I think there are three points of view—that of the consulting engineer, oftentimes, that of the central station representative, and finally the exact operating cost of the plant after it has been in service some years. I have here simply one point to which I want to draw your attention—some years ago Mr. Isaac D. Parsons presented a paper in the Engineering Magazine, the February 1902, issue, in which he gave the average number of pounds of coal consumed per kw-hr., in a large number of plants. I believe there were three apartment houses, three hotels and three clubs, representing in these three classes the most difficult service in the world with which a central station in a large city must compete. I have never seen the accuracy of Mr. Parson's figures questioned, but I have seen them confirmed in many ways, of which Mr. Bolton has just given an instance. He finds they go as high as 25 lb. of coal per kw-hr. generated, including the coal required for heating. The final of the averages is 17.3 lb., and

the average of all, divided by the kw-hr. required, is 15.5 lb. of coal per kw. hr. I think customarily we find in preliminary estimates from 6 to 7 lb. allowed.

In conclusion, let me give you three exact illustrations of the cost of operating private plants in this City. The details are given in my notes, and will be found of interest, because they represent very careful tests which have cost several thousand dollars. The first is a modern office building of 3,000,000 cu. ft. The admitted cost last year, from the books kept by the owners, of light and power, heat, and the elevator service, was $36,085. This is an exact statement. Central station service has been offered, under any guarantee which the owners may require, including the heating of the building, for $27,000 a year; that is, the entire element of fixed cost, which in this case becomes $9,000, may be ignored, and the central station service, plus the cost of heating the building from the boilers on the premises, is identical with the present cost of operating the plant. The second case is a modern hospital, the expenses of which admittedly ran to $24,580, with nothing allowed on the original investment of about $60,000. The authorities of the hospital have been offered a contract under which the total cost of heating, plus the cost of electric current supplied from the street, cannot exceed $22,000 a year. My third illustration, which is the most difficult of all with which to compete, is a large modern hotel—the costs here were taken from the books. The investigation was made by two engineers of note in our city, one jointly employed, and the other employed only by the owners of the hotel. The cost in this case is $41,297. 500,000 kw-hr. were made, and this item of $41,297 includes nothing but fuel, labor, removal of ashes, some repairs, etc., but nothing for interest, depreciation, taxes or insurance. They were made an offer of $40,920 as the cost of steam heating supplied from the building and electricity purchased from the street. There again the entire element of fixed charges may be waived, and yet the two costs balance each other. I think the figures given in my analysis will be found typical upon correspondingly careful investigation of the conditions that exist in practice in large buildings in such a city as New York.

Parker H. Kemble: I think all of us who have occasion to look up the costs of a private plant service, as compared with a public corporation service, should be grateful to the authors of the paper this evening for emphasizing a lot of points that are not usually clearly brought out. The points to which I wish particularly to call attention are in Mr. Hibner's paper, especially Table III. The item of profit is given at five per cent. I do not think any manufacturer will go in o business on the basis of a five per cent profit, with the anxiety and worry and chance of failure, when that profit can be obtained by the purchase of any ordinary good bond on the market. I called up a half dozen manufacturers in Brooklyn and asked them what turn over they

would consider it necessary to have on $15,000, in order to make it worth while to take it up and consider it. The lowest man of the six gave a turn over of 15 per cent, on the basis of five per cent for the use of the money, giving a net profit of ten per cent, or twice the amount given in the paper. The highest man of the lot gave a turn over of 30 per cent, stating that they turned over their money on an average of ten times a year, with a profit of three per cent each time. Between these two extremes, I should say it would be safe to take 15 per cent as a matter of profit. If this is added in to the cost of power, it will bring the cost up to a little over two and three-quarter cents.

Another point, as to the amount of coal—my experience in plants of this size has shown that in the neighborhood of ten pounds of coal is a conservative figure. If that is taken into consideration with the profit matter, it will bring the cost per kw-hr. to 2.84 cents. If any expense is allowed for the time of the manager which he spends in looking after the plant, that of itself will bring the cost, irrespective of the other item, up in the neighborhood of 2.5 or 2.6. Any two of these three items added together will bring the cost of power, based on Mr. Hibner's figures, to over three cents. Any large public service corporation will be very glad to supply power to a plant such as outlined here, with a load factor as given here, for 3 cents per kw-hr. on a term contract, which is the point I want to bring out.

H. H. Edgerton: I have for the last year been paying particular attention to the cost of electric current as generated in private plants.

I have here the data as to costs in one case, that may be considered fairly typical in regard to equipment and results for equal output. The plant is of 460 kw. generator capacity:

Total engine and boiler room expenses: 1909–10		$39,894.00
Total expenses for electric service		12 809.61
Credit for exhaust steam used in heating		3,157.28
Net cost of 461,600 kw-hr.		9,652.33
Net cost per kw-hr.	2.091 cents	
Interest and depreciation, $4,600	0.997 "	
Total per kw-hr.	3.088 "	

The electric service included lighting, ventilating motors and vacuum cleaning service; also 28.4 per cent of the heating and hot water service.

The elevator service, six elevators, pumping service, ice machine, sewage evacuators and remainder of the heating and hot water services was from other than electric power sources.

The cost of fuel (pea coal) was $4.20 per ton. The division of the fuel and labor accounts was based upon a series of engine indicator cards, taken over the period of a year.

I notice that in Mr. Parker's paper that central plant current is estimated, selling price, at about 3 cents per kw-hr. In this locality that figure would not cover interest and depreciation, let alone production and distribution costs.

C. M. Ripley: If by any chance these proceedings of this evening should find their way into the hands of industrial men, and others who have the decision in their hands as to whether they shall make or buy their electricity for their new plant, I would like to have this go on record—that the Commonwealth Edison Company of Chicago of my own certain knowledge own and operate three isolated plants in the basement of buildings. If industrial plant owners, managers and engineers need any further encouragement regarding the earnings of an isolated electric plant I will say that the Commonwealth Edison Company is glad to pocket the income from such, even after paying a fancy rental for the basement space occupied. Some of these plants are equipped with Corliss engines and others with high speed engines; the owners of industrial plants can likewise depend on and profit by similar apparatus designed by the same manufacturers.

H. W. Peck: At the present time, with men designated as engineers in the foreground of nearly every large economic analysis, more papers of the general character of the one presented by Mr. Parker to-night should be given before the engineering societies. Aside from the subject of railroading, there have been very few such papers—too few. We should have in our TRANSACTIONS, for example, an analysis of the principles of depreciation corresponding to Dr. Alexander Humphrey's classic before the American Gas Institute. I regard Mr. Parker's paper as a valuable contribution to our proceedings, outlining, briefly and clearly, the principles appertaining to a certain detail of everyday engineering work. Mr. Hibner's paper is valuable, also, as it discusses a subject which is of great moment to a large number of engineers; and while in most of the individual cases industrial plants are relatively of small importance, the sum total of them amounts to an exceedingly great figure, and the amount of engineering work being expended on them is very great.

Referring to Mr. Parker's paper, certain parts might properly, it seems to me, have been elaborated a little more. Other methods of providing for amortization can properly be mentioned, as, for instance:

1. A yearly sum equal to the investment, divided by the number of years' expected life, should be set aside annually, allowing the variable earnings of this fund to be added to the other earnings of the company.

2. A variable yearly sum, equal to a fixed per cent of the decreasing back value of the plant, may be set aside; for example, 10 per cent of the full value at the end of the first year, 10 per cent of the remaining value at the end of the second, year and so on. This method would never completely amortize the plant, but would more nearly represent its actual depreciation in value, and leave a relatively small amount to be charged off in one sum at the end of its natural life, or, indeed, somewhat earlier.

My own preference is in favor of the first method, although

the choice of methods may very reasonably differ for different classes of business and different financial conditions.

Inadequacy should properly be mentioned with obsolescence, as in general the same considerations hold good for both conditions. Similarly, *business risk* is an element of *fair profit*, though not always associated in one's mind.

In certain points I do not agree with Mr. Parker. I would call attention to the fact that the depreciation rate on certain details, considered by themselves, is not correct when they are considered as part of a plant; for example, a building which might be in excellent condition after 50 years, would, in all probability, not be useful that length of time, nor for a period any longer than the life of the equipment in it. I have in mind an expensive brick chimney and engine room which was discarded in four years' time to make way for a larger one required by increase in the business requirements. In this case the matter of inadequacy would have required a 25 per cent depreciation rate instead of a 2 per cent, which might have been allowed from the consideration that the building would be in fair state of preservation for 50 years. Of course, if this condition had been anticipated, a chimney and engine room of larger capacity would have been installed originally, so that I am not arguing for an amortization rate of 25 per cent, but simply wish to mention one of a number of illustrations of the fact that inadequacy is very likely to be the consideration which will determine the proper sinking fund.

I emphatically disagree with Mr. Parker's statement that "obsolescence, therefore, has essentially no existence for private power plants, even under stress of competition." If I purchase a plant to furnish power to operate my factory, finance it on a 20-year basis, and in five years' time improved equipment can be purchased with double the efficiency of my apparatus, a new competitor will be able to undersell me by an annual amount equal to one-half the power cost. I then have to choose between the loss of one-half the power cost annually, or the unamortized part of my plant, less its sale value. This seems to me very clearly to be the case, in fact, Mr. Parker practically admits it in a following paragraph.

The sale value of the old plant should, of course, be added to the sinking fund and be credited to the new equipment.

The charge of $2,000 for supervision is proper, of course, regardless of the salary actually paid for supervision, unless here again the marginal principle applies in apportioning the time of the superintendent, that is, that a sacrifice of 20 per cent of his time would not sacrifice 20 per cent of the profit of the business.

Under the subject *Fair profit*, it should be noted that items of necessity do not have to carry their own burden of profit; for example, an ordinary business cannot be carried on without artificial heat in the winter. The total cost of heating must be

carried by the profit-making parts of the business, assuming that heat cannot be purchased from a heating company. Thus the various elements making up the cost of heat must be deducted from the corresponding elements making up the cost of combined heat and power before figuring the actual cost of the power alone. This is illustrated well in Mr. Hibner's paper except, possibly, for the considerations following.

I have observed that if 100 tons of coal per month are required for heating a building, and if 100 tons are required for power alone, it is assumed that 100 tons, or possibly 110 tons, to allow for loss in the engine, will be sufficient for both heat and power. Where the requirements so nearly balance this is manifestly not the case, for the heating requirements are distributed throughout the 24 hr. of the day, with a marked peak early in the morning before the business part of the plant begins operation. The power requirements, however, are limited to from 8 to 10 hr. a day, with the peak usually during the warmer parts of the day, or during the late afternoon, just before shutting down the factory, when it is permissible to allow the temperature to drop slightly. This means that the coal for combined heat and power may easily amount to from 150 to 175 per cent of the coal required for either purpose alone.

I do not like Mr. Hibner's use of the expression "load factor" with the limitation of ten hours. I think it is very generally agreed that load factor should be limited to daily, monthly, or annual load factor.

John H. Norris: The following examples of installations of gas engine costs of operation are presented to show the economy that can be obtained even down to small sizes when using the gas engine for power purposes. I have selected a few typical plants running on various fuels. Owing to the fact that the cost for buildings or rent for space varies so much, I have not included in my costs hereafter given any allowance for said buildings or space occupied by the installations.

Plant No. 1 is a 50-h.p. 3-cylinder gas engine direct-connected to a 125-volt direct current generator with a speed of 275 rev. per min. running on natural gas and furnishing an 11-hr. service 300 days per year.

The load on this plant is 15 kw.

Cost installed	$3,500.00
Interest and depreciation	$350.00
Repairs and supplies	175.00
Labor per year	900.00
Total operating cost, exclusive of fuel	$1425.00
Gas bill for year	315.56
Total yearly charge	$1740.56
Total kw-hr. for year	49,500
Cost per kw-hr	$3\frac{1}{2}$ cents.

Plant No. 2 is a 25-h.p. engine belted to a 15-kw. generator and one 20-h.p. engine belted to a 12-kw. generator running on natural

gas and furnishing light and power running at approximately full load; service 16 hr. per day 365 days per year.

Cost installed, $4,200.

Interest and depreciation	$420.00
Repairs and supplies	210.00
Labor per year	700.00
Total operating cost, exclusive of fuel	$1330.00
Gas bill for year	1270.18
Total yearly charge	$2600.18
Total kw-hr. for year	128,480
Cost per kw-hr	2.02 cents.

Plant No. 3 consists of one 65 and one 30-h.p. gas engine furnishing power for a manufacturing establishment running on illuminating gas at 80 cents per 1,000 ft.

Cost installed, $4,375.

Interest and depreciation	$437.50
Repairs and supplies	220.00
Labor per year	360.00
Total operating cost, exclusive of fuel	$1017.50
Gas bill for year (80c. gas)	3279.00
Total yearly charge	$4296.50
Total h.p. hr. for year	228,000
Cost per h.p. hr	1.89 cents.

Plant No. 4 consists of one 100-kw. and one 65-kw. direct-current sets, operated by gas engines running on city gas at 65 cents per 1,000 ft. 11-hr. service.

Cost installed, $12,300.

Interest and depreciation	$1230.00	
Supplies and repairs	600.00	
Labor per year	2000.00	$3830.00
Cost of fuel per kw-hr	1.6	
Operating charges	0.7	
	2.3 cents per kw-hr.	

Plant No. 5 consists of two 75-kw. and two 65-kw. direct-current generating sets operated by gas engines and running on city gas at 65 cents per 1,000 cu. ft.

Cost installed, $23,000.

Interest and depreciation	$2300.00	
Supplies and repairs	1150.00	
Labor per year	3300.00	$6750.00
Fuel cost per kw-hr	1.6	
Operating charges	0.3	
	1.9 cent per kw-hr.	

Plant No. 6 consists of one 40-h.p. and two 18-kw. gasoline engines direct current sets furnishing light and power to a country estate.

Cost installed, $9,580.

Interest and depreciation..............	$958.00	
Supplies and repairs..................	480.00	
Labor per year........................	1500.00	$2938.00
Cost of fuel per kw-hr................	2.025	
Operating charges....................	1.29	
	3.315 cents per kw-hr.	

Plant No. 7 consists of one 15-kw. gasoline engine direct-current set used for lighting service in connection with storage batteries.

Cost installed, $2,500.

Interest and depreciation..............	$250.00	
Supplies and repairs..................	140.00	
Labor per year........................	400.00	$790.00
Cost of fuel per kw-hr................	2.025	
Operating charges....................	1.78	
	3.805 cents per kw-hr.	

Plant No. 8 consists of a 35-h.p. anthracite producer, 28-h.p., 2-cylinder vertical gas engine, 24-hr. service.

Belted to an 18-kw. generator.

Furnishing light and power.

Average load, 10 kw.

Fuel, anthracite pea coal at $4 per ton.

Cost installed, $3,000.

Interest and depreciation..............	$300.00	
Supplies and repairs..................	150.00	
Labor per year........................	500.00	$950.00
Cost of fuel per kw.at 4.00 per net ton...	0.3	
Operating charges....................	0.61	
	0.91 cents per kw-hr.	

Plant No. 9 consists of one 300-h.p. anthracite producer, suction type, furnishing gas for two 100-kw. Allis-Chalmers generators of 60-cycle three-phase, 2300 volts, running in parallel and operated by two vertical gas engines. Fuel, pea anthracite at $4.00 per ton, 24-hour service.

Cost installed, $22,000.

Interest and depreciation..............	$2200.00	
Supplies and repairs..................	1100.00	
Labor per year........................	2400.00	$5700.00
Cost of fuel per kw-hr................	0.3	
Operating charges....................	0.4	
	0.7 cent per kw-hr.	

Plant No. 10 consists of one 400-h.p. double-acting tandem horizontal engine running on producer gas furnished by two 200-h.p. anthracite suction producers driving flour mill by rope drive and grinding a barrel of flour for 8 lb. of coal

Fuel, used No. 1 buckwheat coal.
24-hour service.
Cost installed, $38,000.

Interest and depreciation	$3800.00	
Supplies and repairs	1900.00	
Labo· per year	3000.00	$8700.00
Fuel cost at 7.00 per ton	0.42	
Operating charges	0.3	
	0.72 cent per b.h.p.-hr.	

Plant No. 11 consists of 400-h.p. double-acting tandem horizontal engine direct current 2,200-ton ammonia compressor.

Twenty-four-hr. service and giving 30 tons of refrigeration per net ton of coal, coal being Illinois slack, carrying 38 per cent volatile matter and averaging 10,300 B.t.u. per lb.

Cost installed, $44,000.00.

Interest and depreciation	$4000.00	
Supplies and repairs	2000.00	
Labor per year	4500.00	$10,500.00
Cost of fuel (coal) per h.p.	0.1	
Operating charges	0.361	
	0.461 cent per b.h.p.	

Plant No. 12 consists of a 300-h.p. anthracite suction producer driving a four-cylinder vertical engine direct connected to a 200-kw. direct-current generator furnishing power and light.

Cost installed, $18,000.

Interest and depreciation	$1800.00	
Supplies and repairs	900.00	
Labor per year	1500.00	$4200.00

Fuel used, No. 1 buckwheat; cost per ton, $4.00 delivered.

Cost of fuel per kw-hr.	0.3
Operating charges	0.63
	0.93 cent per kw-hr.

I have a record of a three weeks' run on this plant, in which the following figures may be of interest:

Total kw-hr. furnished	19,368
Elapsed time	480 hours
Per cent running time	36 per cent
Per cent shut down time	64 per cent
Average kw	113.85
Per cent of full load	56.9
Coal per kw-hr., including all standby losses	2.36 lb.

I have also a record of a run of one week in which the average kilowatts were 87.28.

Per cent of full load	43.6
Coal per kw-hr.	3.46 lb.
Per cent of time running	37.2 per cent
Per cent of time shut down	62.8 per cent

In these two runs there has been no attempt to meet test conditions. There are simply the reading of the instruments

and the actual amount of coal supplied to the producer during the time specified.

Plant No. 13 consists of a 150-h.p. anthracite suction producer, furnishing fuel to a 150-h.p. three-cyclinder vertical engine direct connected to a 100-kw. direct-current generator furnishing power and light to a manufacturing establishment. Eleven-hr. service. Fuel, pea anthracite at $4.00 per ton.

Cost installed, $9600

Interest and depreciation	$960.00	
Supplies and repairs	480.00	
Labor per year	750.00	$2190.00
Cost of fuel per kw-hr	0.3	
Operating charges	0.66	
	0.96 cent per kw-hr.	

Plant No. 14 consists of three 200-h.p. producers, furnishing fuel to one 600-h.p. double-acting tandem gas engine direct connected to 400-kw. alternating current generator, 60-cycle, three-phase 600-volt, furnishing power for cement mill.

Fuel, Texas lignite, carrying 8000 B.t.u. per lb. and costing $1.50 per net ton delivered. 24-hr. service.

Cost installed, $40,000.

Interest and depreciation	$4000.00	
Supplies and repairs	2000.00	
Labor per year	3200.00	$9200.00
Cost of fuel per kw-hr	0.169	
Operating charges	0.32	
	0.489 cent per kw-hr.	

Plant No. 15 consists of one 150-h.p. suction producer furnishing fuel to one 150-h.p. vertical three-cylinder gas engine direct connected to a 100-kw. generator furnishing light and power.

Cost installed, $9600.

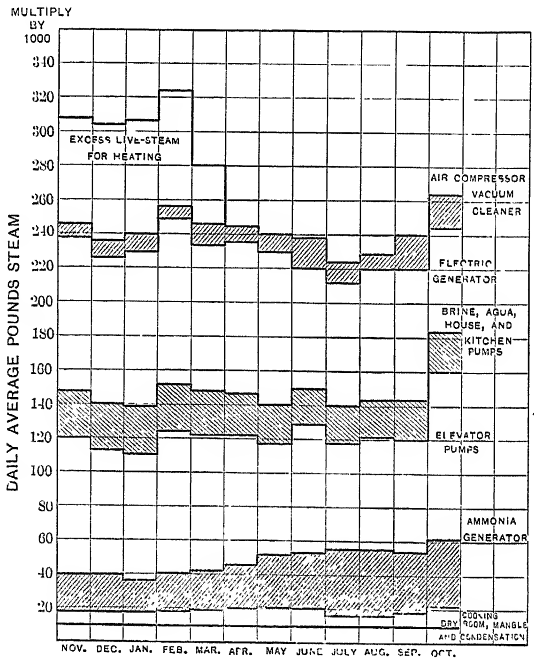
Interest and depreciation	$960.00	
Supplies and repairs	480.00	
Labor per year	1700.00	$3140.00
Cost of fuel per kw-hr	0.17	
Cost of operating	0.4	
	0.60 cent per kw-hr.	

In connection with this plant, I have a record of a 38 days' run which is as follows:

Duration of run	912 hr.
Time shut down	75 hr.
Per cent time running	91.75 per cent
Per cent time shut down	8.25 per cent
Total kw-hrs	38,353
Total lignite supplied to producer	196,520 lb.
Consumption per kw-hr	5.12
Cost of fuel per kw-hr	0.42 cent
Operating charges, as above	0.43 cent
Cost per kw-hr. at 40 per cent load	0.85 cent

Referring to the statement of Mr. Williams, that the gas producer is a very unreliable piece of apparatus, I would like to state that as a matter of fact the depreciation of a gas producer properly run is less than that of a steam boiler plant, and the gas producer of to-day is a very satisfactory and reliable power generator.

Richard H. Tillman: The paper by Mr. Parker on "Fixed Costs" will more than likely bring out sufficient discussion to have its title more appropriately termed "Variable Fixed Costs". Notwithstanding this fact, however, the paper repre-



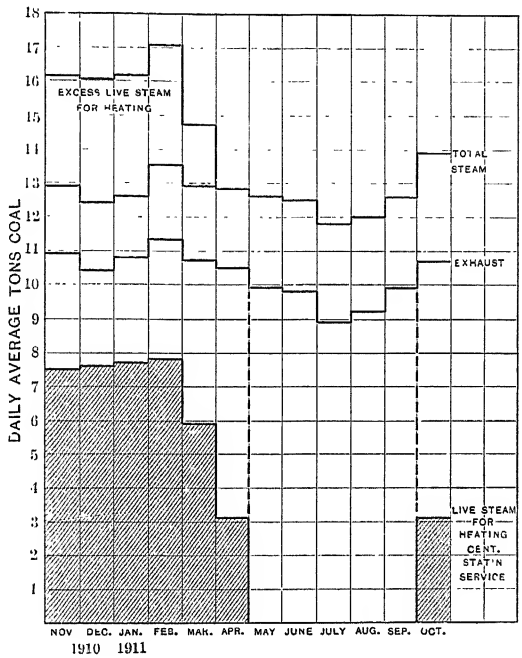
Curve No. 1.—Showing operating conditions. Typical hotel plant Steam distribution

sents the cold facts so plainly that it will be hard to refute the claims made therein. This paper will be the means of bringing out many ideas and will be the base of much good work in industrial engineering.

One item of fixed costs entering into an industrial power plant which has not been brought out plainly in the paper is what we might term "first interest and depreciation costs". When a new factory is to be located the first large expense is made in the power plant equipment. This equipment is usually purchased to supply the total needs of the complete industry

and sometimes, contemplated additions to the factory. It is usually several months from the time the power equipment is purchased before any factory is operated at its full capacity. It is evident that the greater part of the fixed costs begins when the plant is first purchased.

The amount of fixed costs that can be charged against plants in an unfinished condition will, of course, depend on the size and type of construction and machinery used, or the time that portion of the plant is idle. In the case of purchased power, where the power rates are based upon the fixed costs on the actual



Curve No. 2.—Showing operating conditions. Typical hotel plant Coal consumption

power demand metered, the first fixed costs on a new industry will not be so heavy.

In the paper entitled "The cost of Industrial Power" by Mr. Hibner, we find some very interesting as well as valuable points. Most of the figures presented in this paper can certainly be verified by figures from different locations. There is one question which I would like to ask concerning Table II of the paper.

Under the head line "Operating Costs of Power Plants" there are two items, namely "Banking" and "Night heating".

I would like to ask Mr. Hibner what is the difference between these two items, and how are they arrived at.

As mentioned in Mr. Hibner's paper, we find that the actual industrial power plant costs are very indefinite. Also estimates on the necessary capacity for industrial plants have been found to more than double the actual requirements when the plant was put in operation. I have known of instances where the consumption in kilowatt hours of an industrial establishment was estimated by considering the total rating capacity of the boilers for the total time the factory was operated. To demonstrate this let us consider one of the many industries in which Baltimore leads—the manufacturer of fertilizer. The actual costs which we have found to exist in three factories for the past twelve months are as follows:

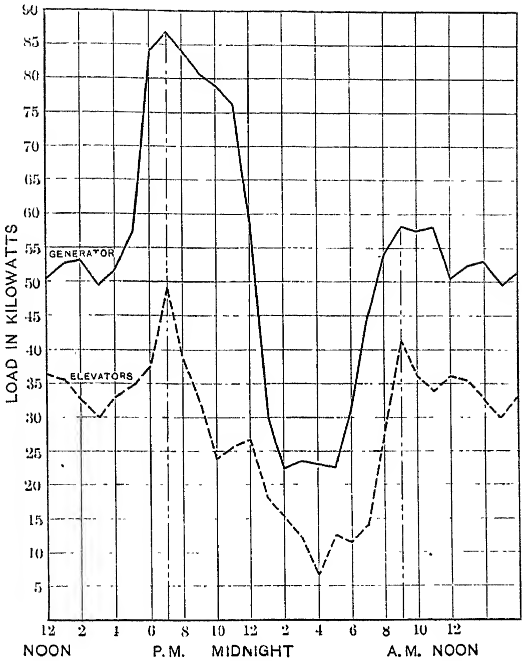
	"A"	"B"	"C"
Connected load	198 h.p.	170 h.p.	350 h.p.
Maximum demand	75 kw.	91.5 kw.	92.5 kw.
Av. monthly consumption	14410 kw-hr.	19118 kw-hr.	10592 kw-hr.
Load factor (10 hr. 26 days)	74 per cent	80.4 per cent	44 per cent
Motor capacities	1–50 h.p.; 1–40 h.p.; 1–30 h.p.; 3–20 h.p.; 1–15 h.p.; 1–3 h.p.;	1–100 h.p. 3–20 h.p. 1–10 h.p.	5–40 h.p.; 1–35 h.p.; 1–20 h.p.; 2–15 h.p.; 5–10 h.p.; 2–7½ h.p.
Approximate output in tons per month	3500	6000	3500

The plant estimated for the column marked "A" included one 200-kw. unit and one 100-kw. unit and a consumption of 35,000 kw-hr. per month. This tabulation shows a high load factor on "A" and "B" factories, and this is caused by the fact that part of the machines are operated 22 hr. per day, while those in factory "C" are operated only 10 hr. per day.

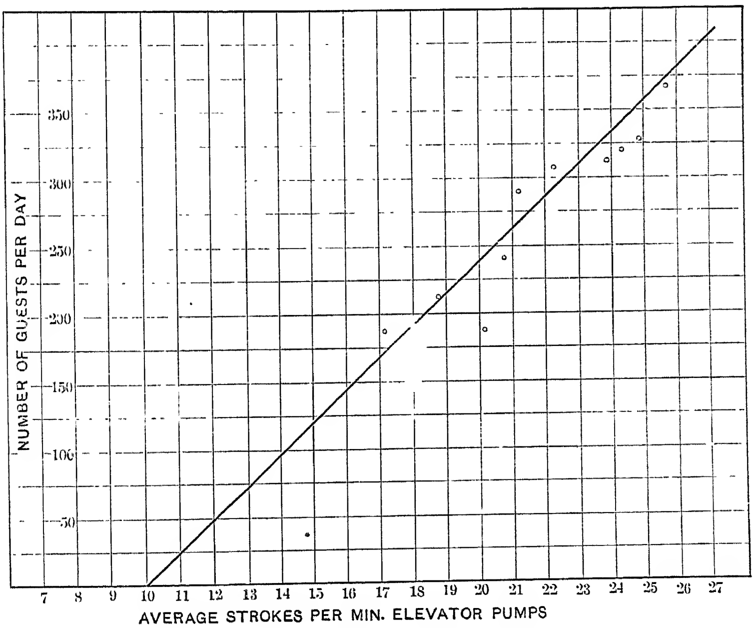
In comparing the labor requirements in these factories with the tabulation given in the papers, I might state that in no one of them is any expert labor required to attend the electrical equipment. An oiler passes through the factory about twice during the day and takes note of the bearings, spending the remainder of the time at other work.

There has but lately come to my notice a forceful instance of how a plant may be over burdened with fixed as well as operating costs, by a biased engineer. I have prepared curves to illustrate how this could have been easily obviated by careful investigation and comparison of plants of similar type; also how the costs entering into the total expense of a plant can be separated.

This plant consists of 525 kw. in generating units and the maximum electrical demand is 90 kw. It is not necessary to comment on the fixed costs of such a plant. By the use of a



CURVE No. 3.—Load showing operating conditions Typical hotel plant

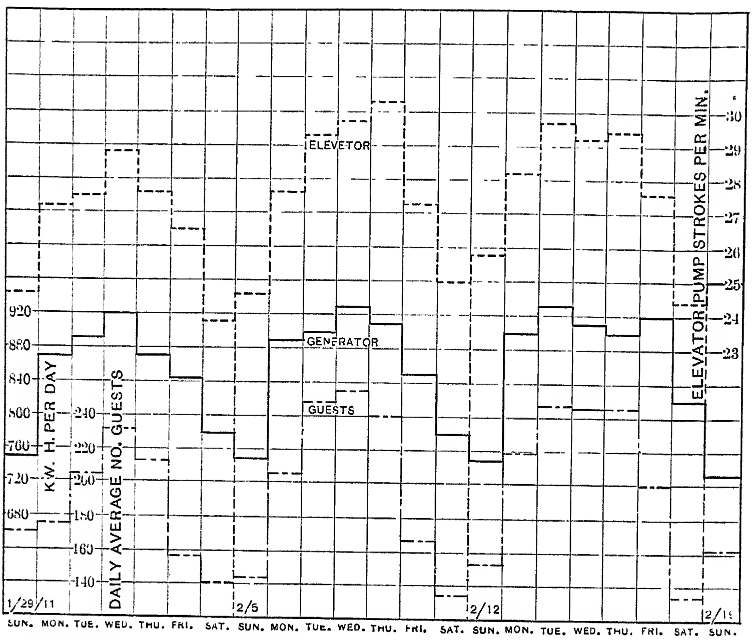


CURVE No. 4.—Operating conditions. Typical hotel plant elevator pumps

condensing apparatus the steam for various services was determined.

The steam distribution is figured on the basis of $8\frac{1}{2}$ lb. steam per lb. of coal, and Curve 1 shows graphically the exact amount of coal used for the various services in the Hotel plant. This far south heating is carried on from about the middle of October until the middle of April, and includes only about 150 days for heating per year.

Curve 2 shows steam represented in terms of equivalent coal value. Total exhaust is also shown, and the difference between



Curve No. 5.—Operating conditions. Typical hotel plant Generator and elevators

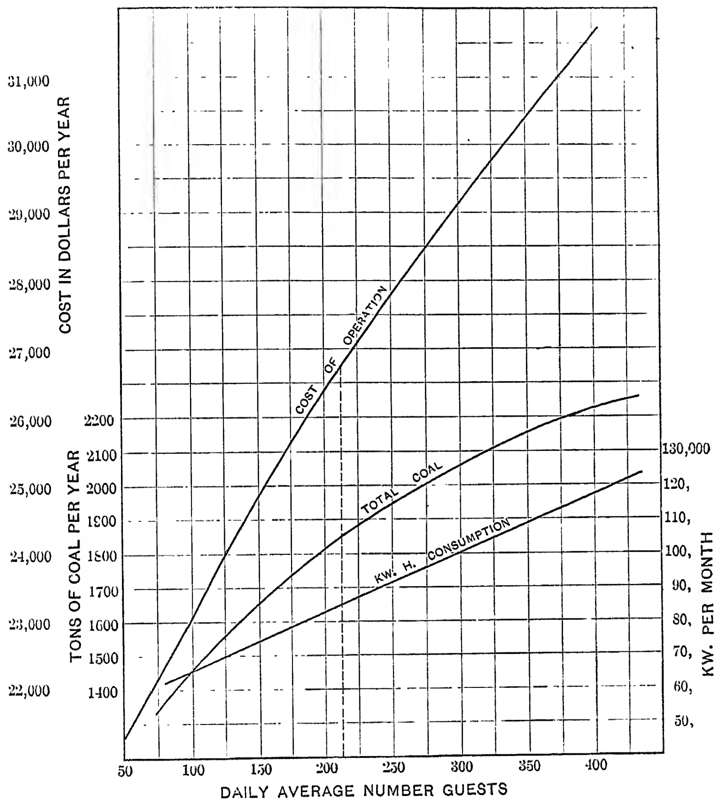
total steam and exhaust gives the live steam used for cooking, mangles, ice machine, etc. The shaded portion represents full value of live steam to replace present exhaust as used in heating.

Curve 3 shows the load curves of the Hotel plant in operation. It will be noticed that the peaks on elevator pumps varies practically with the peak on the generator. The various power requirements of the hotel holds the load up during the day as shown.

Curve 4. In various hotel plants tested it was found that the power requirements varied with the number of guests. If observations are taken over a considerable period of time, curves

can be plotted which establish the working law by which the power requirements for any given month can be calculated when the total average number of guests is known. It is to be noted that when the number of guests is reduced to zero that the pumps are still doing work. This is due to the help, freight elevator, etc.

Curve 5. This curve shows how closely the operation of the



CURVE No. 6.—Cost of operation, central station service
Typical hotel plant

generator and elevator pump depend upon the number of guests. This is a typical business man's hotel. The falling off in the number of guests at the end of the week is characteristic of this type of hotel.

Curve 6. This curve shows the cost of operation. This factor bears a certain relation to the total average number of guests. It is to be noted that the greater the number of guests

the less the variation in cost for a given increase in number, showing that a high load factor for guests is also a profitable thing for a hotel.

W. S. Timmis: The power plant installed at 435 East 24th St. consists of three 250-h.p. water tube boilers, two 150-kw. direct-connected generators with compound engines, one-100-kw. generator, compound engine, and one 50-kw. direct-connected generator, simple engine. Also two $7\frac{1}{2}$-kw. balancer sets.

The cost of this outfit is given as follows:

Boilers, including setting.		
3 250 h.p. water tube	$11190.00	
Engines.		
2 150-kw. compound		
1 100-kw. compound		
1 50-kw. simple	12190.00	
Generators	6100.00	
Balanced draft	2325.00	
Steam Fitting.		
Includes all auxiliaries	6378.00	
Total cost of plant		$38,183.00
Cost per kw		84.85

This plant has been in operation for over three years. It was installed to accommodate a much larger load than it has been called upon to carry; with a capacity of 450 kw., the average load, taking a period of one year, has been 127 kw.

The following table gives the actual cost of running the plant for a period of one year from January 1, 1910 to January 1, 1911.

Wages (cost to run one year)	$5233.84
Coal	4817.69
Water	360.00
Ashes (removed)	223.24
Oil and waste	164.40
Supplies (packing, sheet rubber, pump valves, soda-ash, boiler handhole gaskets, piping, etc.)	159.27
Repairs	263.28
Total	$11221.72
Interest and depreciation on cost of plant $38,183 at 12 per cent	4581.96
	$15803.68

Kw. metered 381,500.
Cost per kw. $0.0294 without interest and depreciation.
Cost per kw. $0.0412 including interest and depreciation.

During the year there were 722 hr. overtime at time-and-half per hr.:

Assistant engineer	75c. per hr.
Fireman	56c. per hr.
Sundays and holidays (5 days and 6 hr.), which makes a total of	$1024.32*

*This item is included in the total amount under wages.

The above figures include the cost of heating the building, the value of which is estimated as follows:

Coal 585 tons	$1949.75
Two firemen 30 weeks, $15 each	900.00
Part time of chief engineer	500.00
Water	30.00
Removal of ashes	90.00
Interest and depreciation on boilers 250 h.p. and distributing panels, $4740.00 at 12 per cent	568.00
Total	$4037.75

Deduct from the total cost of running power plant for one year, $15,803.68.

The amount for heating, $4,037.75.

Cost of running power plant less value of heating, $11,765.93.

Actual cost of current, 0.0323.

The cost of Edison service at wholesale rates for the amount of current generated would have been, $17,660.16 as against cost to operate plant, including all charges $11,765.93. Leaving balance in favor of plant, $5,904.23.

At the time the plant was installed it was thought that a much larger load would obtain.

Stonewall Tompkins: The power plant of the Coney Island & Brooklyn R.R. Co., is not one of the large ones, but may, for this reason, be not less interesting for discussion.

Description of Plant

The power house is located at Ninth Street and Gowanus Canal, Brooklyn. Coal is delivered in lighters from which it is hoisted into storage tanks which discharge by gravity into a car which runs into the boiler room. The coal used is a mixture of No. 3 buckwheat and bituminous, the latter constituting about one-eighth of the entire mixture. Stoking is done by hand. Air pressure under the grates is supplied by steam-driven blowers, the speed of which may be regulated. The burnt gases discharge into a 200-ft. stack, and a nearly balanced draft is maintained by hand controlled dampers. Shaking grates (the back half of which may be dumped) are used under water tube boilers. Feed water comes from the city mains, and is heated in an open heater by the exhaust from blower engines, pumps, etc. The main generators are vertical shaft turbine-driven alternators, and the exciters are horizontal turbine-driven. The turbines exhaust into barometric condensers, having motor-driven centrifugal pumps, and steam-driven flywheel dry vacuum pumps. There are steam-driven pumps for the step bearings, and for the oil-pressure governors of the turbines. The plant operates twenty-four hr. per day every day in the year. There are two daily peaks in the load, the greater one occurring about 6:00 p.m. and the lesser about 8:30 a.m. The effect of the seasons is to make the load heavy in hot weather on account of great traffic, also heavy again in cold weather on account of extra current used

in heating the cars, and in overcoming bad track conditions of snow, sleet, etc.

Each car of coal is weighed as it enters the boiler room. Water is measured by meter on the city supply, (and the cost of water herein given covers not only all evaporated in boilers, but all other water used about the plant). The electric energy is metered at the switchboard, but a small portion of this is afterwards used to drive the circulating pump motors, and is not separately metered. It has, however, been estimated at 3 per cent of the total output of the plant, and therefore the total output of the power house as herein given is 3 per cent less than the actual metered amount.

List of Equipment

2 2,000-kw. three-phase turbines.
2 75-kw. exciters.
2 Barometric condensers.
2 Motor-driven centrifugal pumps.
2 Steam-driven dry vacuum pumps.
2 Steam-driven step bearing pumps.
2 Steam-driven pumps for oil pressure governors.
2 Steam-driven blower engines.
2 Steam-driven boiler feed pumps.
6 600-h.p. water tube boilers.
Boiler pressure, 175 lb.
Primary voltage, 11,000 volts.

It should be noted that the expenses for power herein shown do not include the following items:

Interest on investment.
Depreciation.
Taxes.
Insurance.

Nor do they include anything for the pro rata expenses of the officials of the company:

Power House. Total energy (11,000 volts three-phase) measured at power house switchboard, and delivered to cables for transmission to sub-stations............................26,122,312 kw-hr.

Power House Expenses

Fuel, (41,517 gross tons).......	$81,170.06
Labor........................	51,617.97
Water........................	10,503.53
Lubricants...................	1,724.14
Supplies and expenses.........	4,510.78
Repairs of steam machinery....	9,757.44
Repairs of electric machinery...	2,077.59
	$161,361.51

Cost per kw-hr. alternating current. $0.006084
Cost of coal per gross ton.......1.955
Coal per kw-hr..................3.5662 lb.

Sub-stations. Total energy (575 volts direct current) measured at substation switchboards, and delivered to feeders..................23,065,393 kw-hr.

SUBSTATION EXPENSES

Labor	$14,053.56
Supplies and expenses	203.77
Repairs in stations	472.59
Repairs to ducts	874.77
Repairs to 11,000 volt cables	992.04
Total substation expenses	$16,596.73
Add total power house costs	161,361.51
	$177,958.24
Cost per kw-hr. delivered to the direct current feeders	$0.007715

F. G. Gasche (by letter): This paper deals with a subject so timely and important that I feel impelled to urge its widest distribution. The author has made reference to the small plants particularly, but the principles are frequently of general application, and it seems that some of the larger power plants could have been studied to great advantage by methods proposed by Mr. Parker.

The observations concerning " investment " and " interest " cannot be emphasized too strongly, as many additional responsibilities are assumed as soon as a sum of money is appropriated for a given power plant.

The element of " depreciation " is unquestionably subject to variant views, but the evidence of past experience of many engineers would indicate that depreciation " rates " are generally too low and this for a reason quite foreign to the physical permanence of an engine or other part of a power plant equipment. I refer particularly to the rapid changes in method or process which characterize an industry, thus making a power plant obsolete so far as its primary functions are concerned. This may be illustrated more clearly, but I would urge that many industrial power plant elements should not be credited with a useful existence of more than ten years since they may be wholly unsuitable for the purposes of a new business. To illustrate, twenty years ago the simple, vertical, long crosshead type of blowing engine was installed at a group of four blast furnaces. About eight years after, half the group of engines was replaced by larger machines with large steam cylinders, so as to operate them as disconnected compound units. In fifteen years time from the start, they were practically superseded by improved forms of compound engines. About two years ago the new engines were " assisted " by gas driven blowing engines using blast furnace gas, with the implied intention of displacing all steam blowing engines. Now arises the " specter " of the turbine driven turbine blower to set all finance of the power plant " agog " in view of the possibilities. The point I wish to emphasize from this is that fundamental changes in the iron and steel business imposed these changes and not the mere " obsolescence " of the elements of the power plant. Nevertheless, they had a short life. Other lines of industry, not excepting the

business of furnishing electric current, have exhibited similar crises in their development.

There is another element of growing importance in the finance of power plant investments which may for the want of a better name, be called "insurance on reliability". This consists of the aggregate of annual charge that should be set against the gross earnings by virtue of the presence of "spare units", or duplicate equipment of boilers or other apparatus, the purpose of which is to insure uninterrupted service of the plant for any loads that may be assumed. In some cases a full examination of this "reliability" charge indicates that a mistake can be made in the installation of prime-movers of excessively large capacity.

For many lines of industry there are periods of enforced idleness so far as a part of the power plant is concerned, and it is somewhat surprising to note their influence on the power plant finance since the accumulation of interest and similar charges is continuous.

The ultimate result of the examination of the finance of power plant investments will consist in the statement of a series of numerical items affecting the final numerical values of net returns on the investment. Consequently any consideration involved in such analysis, must be capable of measurement in terms of numerical dollars.

A continuance of the study of the subject as illustrated by the paper of Mr. Parker, will ultimately lead to a consensus of opinion as to the nature of the elements entering the problem, and to a knowledge of the laws controlling their effects as illustrated by the "marginal principle" proposed by Mr. Parker. We may hope for the ultimate development of the algebra of finance calculations as a necessary preliminary to proper numerical substitution. Finally, and most important, the selection of interest rates, amortization rates, and all similar items must be established in accordance with legal and geographical restrictions, to say nothing of the attitude of banking interests whose ruling would be almost a finality.

Bearing on this, there is great danger in applying a greater interest rate to the formulas in appendix B, than banking concerns would allow for such loans bearing interest compounded semi-annually. This would seem to limit the interest to 3 per cent or at the most, to 3½ per cent, corresponding to the usual savings bank allowance. Certainly the amortization period cannot be calculated with the formulas of appendix B, with the legal rates of interest for time loans applied.

William B. Jackson (by letter): There is no doubt that the cost of power as generated by isolated plants is usually underestimated by those having such plants in charge. This is likely to be due to a combination of several causes.

It is usually difficult for the management of a mill or factory to fairly recognize charges that should be made against power

generation on account of the work required of the purchasing department of the mill and on account of the proportion of the effective usefulness of the management diverted from the regular business of the company. The former may be of minor importance, but it is likely not to be negligible, while the latter may be of material importance since it diverts the attention of the management from the prime business of the property. An effective management should have sufficient work in developing the business of the company to fully absorb all of its effective strength and resources.

Likewise, it is almost impossible to obtain recognition of extraordinary costs that are incident to an isolated plant, such as those occasioned by uncertainty of coal supply as regards cost, quality and quantity, expense on account of labor strikes, and the uncertainties of the labor market, the occurrence of accidents occasioning extraordinary expense not covered by ordinary forms of insurance, and other like expenses.

If the management costs and the costs occasioned by extraordinary occurrences are fairly taken into account, they are likely to prove a very respectable proportion of the total cost of power generation, and in many instances, I estimate they will be 10 per cent or more of this cost.

I find that the average mill owner who is operating his own power plant, has little definite knowledge of the actual amount of power that he is using. There is the same tendency to over-power a mill when driven by a steam engine as is so noticeable when electric motors are used, and there is an inclination to consider the full rated horse power of the engine as representing the power requirements of the mill. Also, there is usually small appreciation of the comparatively low load factor incident to the operation of most factories or mills, so it is natural that there should be a tendency to over-rate the amount of power being used, and therefore, to under estimate the cost per unit of power.

It is an extraordinary superintendent of a factory steam plant who will seriously combat such misconceptions regarding the cost of the output of his plant, since both pride and policy lead him to accept the lowest plausible figure that can be arrived at as the cost of the output of his department. In many cases, there is honest belief in unreasonably low figures for cost of power. This may be illustrated by a case wherein the management of a mill fully believed they were producing twenty-four hour power for 310 days in a year at less than $20 per indicated h.p. yr., that is, per 7440 h.p.-hr., and they had figures to substantiate this belief. By the results of a carefully organized and conducted test of the plant, with an accompanying complete study of the conditions, they were clearly shown and fully convinced that they must add 50 per cent to the cost they had theretofore accepted as a true one. This was an unusually well-conducted isolated plant operating a large cross-compound condensing engine.

A serious difficulty in the way of obtaining a clear conception of the relative costs of industrial power by different isolated plants, is the uncertainty as to what are the relative conditions under which the power plants are operating. If intelligent comparisons are to be made, it is not sufficient to know the cost per h.p-hr., or per h.p-yr. These mean little in themselves except as related to the plant to which they refer, and under particular load conditions. It is impossible to intelligently compare costs or to obtain a true understanding of what the costs for power really mean without having a knowledge of the costs per h.p-hr., subdivided so as to show the costs of fuel, for oil and waste, for repairs, for boiler room labor, for engine room labor, for insurance and taxes, for management expense, for unforeseen contingencies, for depreciation and for interest, and the basis upon which the two latter are determined must be known. In addition to a knowledge of these costs, an understanding of the operating conditions must be had, including the cost and quality of fuel, the cost of water, how many hr. per day the plant runs and how many days in the year, the variations in load during individual days and from day to-day, the size of the plant, the ratio of the average load to the maximum load of the plant, and the ratio of the maximum load to the economic full load capacity of the boiler plant and of the engine plant.

With these data, the relative performance of the plants as affected by their construction and operation may be determined.

The above seems a formidable array, but any comparison of plant costs becomes less and less valuable as the subdivisions are omitted, until the point is reached where merely the total cost per h.p-hr., and the size of the engine are known, when the data becomes substantially worthless for comparative purposes. It is thus seen that published costs of power, unless accompanied by very considerable data, cannot be valuable as giving a true understanding of the cost of power. As an illustration of this, had the load factor in the plant heretofore referred to been half as good as it was, the cost per h.p-yr. 7440 hr. would have been 50 per cent greater than it was found to be. This is assuming the same running hours for the plant and the same uniformity of load during individual days.

R. Tschentscher (by letter): The subject discussed by Mr. Parker treats of a matter concerning which there exists considerable misinformation and a material lack of appreciation of the various details. It can truely be said that the proper appreciation of " fixed costs " is decidedly limited among engineers and business men. The paper specifies a reference to industrial power plants but it is very probable that the remarks made and the subject treated apply to all power plants, as it appears to the writer manifestly illogical to assign factors governing a return value on the dollar invested in one plant materially different from those for another plant. In arriving at the cost of power, the same elements are in evidence as exist in arriving at the cost

of any other commodity, be this commodity overalls or transportation. The readily determinable operating costs—fuel, upkeep, operating labor, etc.—are too frequently given serious consideration to the exclusion of the consideration of the really more important elements comprising fixed charges. It is frequently factors comprising " fixed costs " which govern the success or failure of an enterprise, be it the generation of power or the handling of transportation. The proper determination of these fixed charges is much more difficult of analysis than that of the operating costs and leads to greater erroneous deductions.

In connection with the matter of " investment " it must be appreciated that the investment charge may vary from year to year, *i.e.*, for example, a 10,000 kw. plant in a certain locality may represent a total investment charge (equipment, land, buildings, engineering, erection, etc.) of $1,000,000. Within five years, the value of land may have increased 25 per cent. Building material and labor may have increased a like amount so that replacement of the building would be increased 25 per cent. Cost of copper, iron and other raw material may have so increased that to reproduce the plant would require an investment of $1,250,000. This, of course, would increase the total amount of taxes, interest, depreciation, etc., which must be considered. The writer believes that the consideration of this feature must be given due weight in the determination of the installation to be made. It is possible that the appreciation of the investment may be such that the fixed charges due to this appreciation may be so great as to offset the gain in operating cost of one installation over that of a less expensive installation.

The definition of depreciation given by Mr. Parker is not as fully appreciated as it should be. The determination of the proper depreciation period is an extremely difficult one and as this item is the largest of those constituting " fixed charges " it deserves the greatest consideration. For example, what is this period for (*a*)—a high grade high pressure steam turbine plant, (*b*)—a blast furnace gas engine plant, each installed during 1910. The depreciation period will depend to a considerable extent on the number of spare units (making investment high but repairs and actual depreciation less) and also upon the operating time of each unit. In other words, the actual depreciation period (considering this period in this connection as the " worn-out period ") will be longer in a plant where the various units are operated on a 10-hour basis than where they are operated on a seven-day-per-week 24-hour basis. The question of the efficiency of the operating labor is also a determining factor of the question of depreciation. A plant may be located where, either because of ignorance on the part of the management or on account of local considerations, the equipment is handled by inefficient operatives. This not only affects operating costs but also the depreciation period. Other factors may enter, all of which indicate that the determination of the proper depreciation period is largely a local one.

In an operating plant, the depreciation rate may be suddenly altered due to a material improvement in economy by the addition of other equipment to the existing plant. For example, the non-condensing reciprocating engine (and in many cases the condensing steam engine) has, during the past few years, had its economical life extended by the advent of the low pressure turbine, the combination of the reciprocating engine and the low pressure turbine giving a materially improved overall economy at a comparatively small added investment charge. Low pressure turbines are, in the majority of cases, installed in reciprocating engine power stations so that land and building charges are distributed over a materially increased installation. This same consideration may, in the future, be applied to the depreciation period of a gas engine plant in which, by the installation of low pressure steam turbines operating from boilers which utilize gas engine cooling water and the gas engine exhaust as sources of heat. The writer believes that subsequent events will show this item of depreciation to be in error more frequently than any of the other estimated charges, either fixed or operating and it therefore behooves commercial engineers to give the matter the most comprehensive investigation.

Mr. Parker, in treating of the subject of "supervision" states in effect that the plant should be charged with uneconomical supervision. The usual manager, particularly the manager of an industrial plant, may not have sufficient knowledge to properly handle or supervise the power plant installation. Because of such a limited knowledge, more of his time is required than if especially trained supervision were employed. This specially trained supervision could, in most cases, be obtained at a lower rate than the rate being paid the manager and therefor the supervision charge would be materially decreased. It appears unfair therefore to charge the plant with more than the cost of proper economical supervision other than that of the local manager. The effect of this special supervision will also be to reduce the total investment because of the superior knowledge of the trained supervisor leading to economies of which the local manager would be ignorant. If proper supervision is not employed, then it appears to the writer that an additional item of fixed charge should be incorporated entitled "bad management" as an exhibit for future comparison.

C. A. Graves: The writer would like to emphasize the point brought out by Mr. Hibner regarding the selection of a competent engineer to advise in regard to the power plant installation.

This engineer should not only be familiar with power plant equipment, but also competent to advise in regard to the layout of the machinery, shafting and motors. The industrial manager is interested, primarily, in the power cost of the manufactured product rather than the cost per kw-hr. and, while a power plant may be installed to produce a certain number of kw-hr. at a rate

of, say 3 cents, if the proper care had been exercised in installing the motor equipment, a smaller amount of power would have turned out the same amount of manufactured product at a lower cost though the cost per kw-hr., may have been increased to $3\frac{1}{2}$ cents.

Power, whether purchased or generated, should not be wasted, and to prevent waste, attention should be given to the laying out of group or individual motor drive in such a way as to balance the shafting friction against the motor friction or efficiency. Many installations are over motored, and it is also a common error to take the sum of the average motor loads as the average load at the switchboard. The switchboard load, however, is less than this sum, the difference depending on the number of motors and the class of the work; and switchboard watt-hr. meters will register considerably less current than is usually estimated.

Another common mistake is to give as the maximum demand, the sum of the estimated demand for power and the demand for lights, forgetting that the peak load for power in most industries comes about 10 or 11 a.m. and that the load is below the average at the time the lights are turned on around five p.m. These abnormal estimates as to the maximum demand and kw-hr. consumption are favorable to a private plant in most cases.

Now, if in taking up a new proposition the layout of the shafting and motors are considered first, and the question of the purchase or manufacture of power taken up after the machinery has been laid out in the best possible manner, it will be found that central station service in the majority of cases will be best suited for the case. Another point which should be considered is the fact that the price of coal is tending to increase, or the grade to decrease. This means that the cost of power will tend to increase in a private plant. On the other hand, the tendency of central station rates is to lower, because the station load factors are improving; the increased cost of coal having but little effect on the central station's cost of delivering power, because it is so small a part of their total cost of serving their customers; so that within a few years proposed private plants will be generating current at costs higher than it can be purchased. This brings us back again to the amount to allow for obsolescence: and the question should be "How many years will it take before the central station price reaches the cost of generating in the private plant."

It seems to the writer that the central station men think that the consulting engineer will always advise an isolated plant because some plants operate cheaper than the quoted rates, and the consulting engineer believes the central station man wants to get every private plant shut down because some plants operate cheaper on street service.

At the rates quoted by central stations there is a portion of the private plants in their locality which can operate as well or better

on the central station service; there is a portion of them which operate at a little lower rate than that quoted; and there is a portion which operate at a considerably lower rate than quoted.

Central stations, as their business grows and the diversity factor increases, are making rates which will secure to them the most profitable business, and many loads which are good for private plants are better for central stations, so that a certain portion of these private plants will be shut down at each reduction of the central station's rate.

Frank F. Fowle: Mr. Parker's paper presents some of the phases of a very live question which is present in nearly every locality where central stations are campaigning vigorously for new business. The issue is the central station versus the isolated plant—not a new problem, but one that promises to remain with us indefinitely and one which constantly reveals new angles.

The owner, or prospective owner, of an isolated plant is the person who most deserves sympathy, for he is beset on one side by the central station man and on the other by the manufacturer of isolated plant equipment, each of whom is determined to have his business, at almost any cost. In the midst of this keen and sometimes bitter competition, it is not to be wondered at that the owner is perplexed over the extravagant and conflicting statements often set forth by each side. This is clearly a situation wherein the disinterested consulting engineer can be of the greatest service to the owner. In many cases the owner avails himself of such service; and again he decides the issue himself, often to his ultimate loss.

The central stations and the manufacturers, recognizing the owners' need of engineering advice, are now generally equipped with sales engineers, or men in an equivalent capacity, whose services are tendered without direct charge. Without denying the expediency of such a plan from the sales standpoint, it is important for the owner to see that such advice comes from partisan sources and he ultimately pays for it, although perhaps not realizing that fact.

Both sides sometimes represent to the owner that he needs no consulting engineer, because their engineers are equally qualified to advise him, with the benefit (apparently) of no expense on his part. Frequently the owner accepts this proposition and relies entirely upon such advice. For his own protection, however, in such a case, he should have the plans and estimates thus prepared submitted to a disinterested engineer for the purpose of checking them and passing on the question of economical operation.

The position of the sales engineer is clearly partisan, for he cannot justify himself to his employer unless he secures business which would not otherwise be secured—and his work thus partakes of a commercial character in a large degree. It is also considered legitimate commercial tactics to so plan the owner's installation, whatever it may be, that he will find it inadvisable

or perhaps very difficult to change his policy after it is once adopted.

This implies no fault-finding with existing practices, because every business man is presumed to have sufficient business acumen to protect his own interest, either personally or through those whom he retains. At the same time it is quite proper to point out the results which often attend such practices where the owner is unqualified to pass on the issues and fails to avail himself of advice which is neutral with respect to the competing interests. The owner is the one who must assume the risks and bear the losses, if any there are.

A study of Mr. Parker's paper brings out clearly the importance of considering and weighing carefully every item of cost, under each operating assumption. The matter of depreciation is of course vital, and should no more be over-estimated than under-estimated. The use of the term amortization in the sense of physical depreciation conflicts with usage which has hitherto obtained. The term depreciation implies the shrinkage in value of all physical property, while amortization covers intangible capital, such as franchise cost, organization cost, licenses with a fixed term, etc. In the present case, under the definition just given, amortization would play practically no part.

The method of securing a depreciation fund which Mr. Parker discusses, by the accumulation of a sinking fund from semi-annual increments at compound interest, is not universally accepted as a satisfactory theory of depreciation. An account of some discussion on this subject by the writer will be found on page 796 of the October 6, 1910 issue of the *Electrical World*. The issue here is between the sinking-fund curve and the straight-line theories of depreciation. The difference is not consequential in relation to the average annual assessments to create the reserve fund, but concerns the present value of the plant at any intermediate stage of its life. There is a marked difference between the methods in the last respect, with numerous arguments in favor of the straight-line theory. The latter is considerably the more conservative of the two and it accords most nearly, in the writer's opinion, with the encroachments of true physical depreciation and the corresponding shrinkage of serviceable value. The straight-line method assumes compound interest on the accumulated fund, just as in the other method.

The marginal theory of investment return is important to consider, of course, but Mr. Parker's deductions from it can perhaps be carried further. In general it may be said that the whole investment in an industrial enterprise consists of plant or property, raw material and stock on hand, product in the course of manufacture, finished material and stock on hand, furniture, fixtures, tools, teams, etc., and liquid assets or working capital. The power plant, as a profitable investment, is no different from other property which can be rented. For example, if the average

profit from the business is quite high, and an equivalent interest rate be applied in computing the cost of owning, say, a warehouse, it is almost a foregone conclusion that it will be cheaper to rent than to own one. And so on, any property or plant which can be rented will generally be cheaper than ownership under a very high rate for the use of capital—that is, the capital can be used more profitably in the enlargement of the output capacity or the sales organization.

On the other hand, if the rate of return is low comparatively, the ownership of much property and plant may be an economy and the lower the rate, down to the usual return on safe investments, the more plant it will pay to own. But, in the first case the concern's credit will be much better than in the second, under like management, and the needed capital would be attracted, whereas in the last case the capital might be difficult to get—which shows the anomalous results of the marginal theory as thus applied.

Mr. Parker's discussion of the curve in Fig. 1 of his paper is extremely interesting, and the conclusions drawn from that particular curve seem to be sound. But it is quite obvious that the curve may take some other form and thus modify or alter the conclusions. It is also noteworthy that the growth and expansion of an industry is not alone a matter of capital; it is also dependent upon capable management and salesmanship and again upon the existence or creation of a market, with possible competition. Any business or industry which earns 20 per cent net for a long series of years, through successive periods of prosperity and depression, is remarkable and indeed the exception. It is reasonable to suppose that such a business is a protected monopoly or one enjoying quite exceptional advantages. Ultimate competition may conservatively be expected and such a result tends always to depress prices and reduce the profit.

The prime requirements of a growing business may not be so much a matter of capital as one of aggressive salesmanship; and if the net returns are large, it is obvious that the new capital thus created can be returned in part to the business, if needed. The concern which owns a well constructed plant, equipped for economical operation, is the one in the strongest position to weather a period of depression or resist competition. Low production costs admittedly may not be imperative when business is at its height and profits are large; but the inability to attain low costs may be disastrous when conditions change.

It seems to the writer that it is more conservative to assume money at 6 per cent, or even 7 per cent, and compare the economies on this basis, leaving it to the owner to decide where his capital can be used most advantageously. The owner is the final arbiter, in any case; while the function of the engineer is to set the real facts clearly before him. A decision not to install an isolated plant when, for example, the investment will earn 10 per cent, while the industry in question earns 15 per cent, is

not fundamentally a question of the comparative economy of the central station service versus the isolated plant, but one which concerns the supply of and demand for capital, and the price at which it can be had, in view of the risks involved.

One more feature of Mr. Parker's results is worth careful study. The results of Table III show quite a saving in favor of central station service. On the isolated plant side there are several items which are perhaps open to discussion. The assumption under emergency service that there will be four days shut-down per month seems excessive; in fact the need of emergency service is open to question, and Mr. Hibner, in the comparison in his paper, assumes none. When the plant units are subdivided there ought to be a very small chance of full shut-down. The allowance of $1,000 for manager's time seems like rather expensive supervision, and it may be noted that no such expense is carried in the other account, which seems hardly fair. Clerical expense at fifty cents per hour is also a rather high item. The rental value of the floor space, at one dollar per foot, may be proper of course, but it is high for many industrial plants. Revising the table and taking fixed charges at 12 per cent, equal to 6 per cent interest, 3 per cent taxes and insurance and 3 per cent depreciation, which are fully ample, it would appear about as follows:

	Central station	Isolated plant
Fuel	$1380	$2290
Ash removal	16	25
Labor	1080	2780
Supplies and repairs	160	366
Water	12	60
Electric service	6259	
Elevator service	415	415
Fixed charges, 12 per cent	384	2304
Supervision	200	500
Clerical expense	25	150
Rental of space		500
	$9931	$9390
Saving		541

This result is in considerable contrast with $2,816 on the opposite side of the balance sheet. The showing in favor of the isolated plant is not marked, but it would probably increase with the growth of the industry and the size of the plant. The owner's decision is not necessarily in favor of the isolated plant, for reasons before given; but a statement in such form is at least

conservative and it leaves with the owner the question of deciding where to use his capital or his credit to the best advantage.

In addition to my remarks on Mr. Parker's paper, in relation to the interest rate to be used in computing fixed charges, which apply also to Mr. Hibner's paper, there are a few points of further interest.

He emphasizes clearly the influence of the uses for exhaust steam, which is often the factor that really controls this question. In fact, when the industry uses steam in considerable quantities in manufacturing processes, in addition perhaps to heating, it is very difficult if not impossible to show superior economy for central station service. Power in that case is essentially a very cheap by-product. When there is little or no such use for steam, on the opposite hand, central station service is ordinarily the cheapest by a considerable margin.

In some cases another feature presents itself which has an important bearing on the net economy. This is the possibility of selling exhaust steam or electric energy from an isolated plant to neighboring industries or business concerns, or perhaps to tenants on the same premises. The revenue thus derived must be in excess of the bare operating cost for the service rendered, of course, or it will represent a loss; but it will usually show some profit and diminish the fixed charges. This plan will be most profitable where some diversity in the different demands is present and where the retailed steam or power is not of sufficient quantity to necessitate a very material increase in the size of the isolated plant. The latter cannot ordinarily compete with wholesale rates for electric energy unless the exhaust steam is needed in industrial processes or can be sold; neither can it afford to distribute either steam or power to any great distance. But in a compact district the sale of by-products may show considerable profit.

In comparing tables I and II of the paper it is notable that 5 per cent profit is included in the fixed charge in the second case, but not in the first. As pointed out in connection with Mr. Parker's paper, there is no reason why the power plant, as an investment, should be put in a class by itself and assessed with an interest rate equal to the average net profit on the whole industry. The same rule should be applied in table I to the heating plant, but preferably not to either plant. Applying it to both plants, it is obvious that the higher the interest rate the greater the disadvantage under which the power plant is placed, because it represents a much larger investment than the heating plant.

Taking away in Table I the 5 per cent profit, amounting to \$575, leaves the net additional cost of power over heating as \$4926 or \$0.0205 per kw-hr. This compares very favorably indeed with wholesale rates for electric energy. The central station rate given in table III of Mr. Parker's paper, with slightly larger demand and consumption, is \$0.0247 per kw-hr.

Taking away the 5 per cent profit reduces the unit cost about 10 per cent.

Similarly, taking away the profit in table III, amounting to \$845, reduces the unit cost to \$0.0217 per kw-hr., or about 13 per cent. This does not affect the question of comparative economy, however, between steam and producer gas, except in a small amount.

Looking at this whole question in a very broad way, it appears from the standpoint adopted here in the case of the isolated plant that the more profitable the industry the less the economy of production need be considered. On the face of things this may seem true, but in terms of gross costs and volume of net returns it is not true. Prosperity begets extravagance and from a state of great prosperity many propositions can be deduced theoretically which are largely artificial. For the ultimate gain of the community the central station ought to acquire all business which conservative economy justifies it in having; at the same time the acquisition of business which can be handled most economically by an isolated plant, is an economic burden in the end.

H. G. Gille, Thomas M. Gibbes: We have gone over Mr. Parker's paper somewhat in detail and feel that he has covered the subject very thoroughly. There are, however, a few points that cannot be emphasized too strongly.

Our experience is that industrial plant owners rarely if ever consider anything in the form of investment except the engine and generator. We therefore feel that the items enumerated by Mr. Parker should act as a guide for working up the investment of any industrial plant.

The item of insurance is a matter of great importance both in industries where inflammable material forms the part of the industry and also where a life hazard is contracted, such as in department stores and public buildings.

Interest on investment, depreciation and obsolescence are thoroughly covered and need no comment.

Supervision and fair profit are probably two items that are rarely if ever considered in the cost of producing power. A parallel case would be the machine shop, they would not consider for a moment installing a milling machine or a gear cutting machine if the amount of money saved on the product of these machines amounted to only a fair interest on the investment of machinery, as no business could exist if a profit was not earned on top of such interest.

R. Norsa: There is one point in Mr. Parker's paper that I will briefly discuss; that is the straight line formula which has been assumed to represent the *investment* cost in a plant. The author has pointed out that the linear equation $\$ = A + B \times \text{h.p.}$ is only roughly true. But, as a matter of fact, we start out with this approximate representation of the investment cost, in order to come to a practical application on the sale of electrical energy;

therefore it seems very important to investigate if the above expression is sufficiently rigorous.

Now this question of cost seems to me much more complex than can be represented analytically by a first degree equation, or graphically by the corresponding straight line. Of course no law of cost is susceptible of reduction to a mathematical form. Only in a few cases some theoretical investigations are possible, as *e.g.*, for the prices of some machinery.

Thus for a line of transformers of a given design and type, it may be shown that the weight of active material increases approximately as a certain power n of the rated capacity, and it may be assumed to vary according to the equation

$$\text{weight} = \text{constant} \times (\text{kv.-a.})^n$$

This would be a linear relation if $n=1$. But if in all transformers of the above line, induction and current density are the same, that is if the losses per unit weight are constant, then n is approximately equal to $\frac{3}{4}$. Consequently the law is not linear but parabolic. As regards the cost, the law will not be very different, and therefore we see that with the increase of capacity, there is a decided saving in weight and consequently a gain in cost. This well known example has been recalled only for the purpose of showing that, even in theory, the straight line formula does not generally hold.

If now we consider the investment in a plant as a whole, the law of the cost becomes very complicated; this law will generally not even be uniform and is not mathematically determinable. We may however admit that a mathematical expression may have some value if it approaches the average conditions, and we may agree that for a plant of a given capacity the *actual* cost may fairly be represented by a fixed expense A and a cost B for each kilowatt. But if we assume A and B as constants and we write

$$\$ = A + B \times \text{kw.}$$

then this equation is supposed to represent the *law of investment cost* in the above plant and consequently it may be applied also to an additional investment, or in other words we assume for each added kilowatt the same cost per unit B, as given by the analysis of the present plant. Now if it is not easy to predict generally what investment will be required by each added kilowatt, we may however state that the cost of the added capacity will very likely be different from the present. If the addition does not require some substantial modification, the added capacity will generally correspond to a lower cost B per unit. Practically we may attempt to follow roughly the law of cost, by saying that the investment is made up of B_1 dollars for each of the first K_1 kilowatts, *plus* B_2 dollars for each of the next K_2

kilowatts and so forth, being $B_1 > B_2 > B_3$ . . . . etc. That is, the coefficient B is no more a constant but varies according to a sliding scale depending on the capacity.

We have above been discussing the cost as regards the investment per kilowatt of central station capacity. Now when we come to examine the sale of energy, one of the elements on which we must fix our attention is (as Mr. Parker already pointed out) the value of the service as determined by the cost of securing an equivalent service in some other way, for example by a private plant. As regards the investment costs of isolated plants, we may now repeat exactly the same considerations, and consequently we shall see again that a straight line formula is not suitable to express the investment costs of these plants; but we shall find as before that the cost B per kilowatt decreases with the increase of the capacity.

On the other hand it is also well known, that with increasing demand of a consumers plant, the cost to the central station of having the service ready at his premises generally increases *with decreasing rapidity*.

The foregoing remarks have been confined to the investment cost and the conclusion may be expressed very briefly. Mr. Parker has very clearly shown the opportunity of a gradation of the B charges on account of the seasonal diversity depending on the seasonal demand of different consumers and also on account of the daily diversity depending on the daily demand at the time of the peak. But as the coefficient B is not a constant, a still further gradation of the B charges, according to greater or smaller demands, should also be considered.

Discussion at Boston, March 22, 1911

Henry D. Jackson: I have read Mr. Parker's paper with a good deal of interest, and in this connection one point strikes me particularly, and that is that if the fixed charges are to be handled by the sales agent of the central station as indicated in this paper, there seems no good reason why the fixed charges on the central station should not be handled in a corresponding way. Certainly the central station has to figure on the profit ratio if the industrial plant has to; and further the amortization rate in a central station is higher than in most industrial plants, for the machines are usually far harder worked and also are scrapped much earlier in their life. These points taken into consideration, there seems no reason to believe that the fixed charges against a central station should be much if any less than against an industrial plant. I have figured that the

Marginal interest would be	5 per cent
Amortization practically	5 per cent
Taxes and insurance	2 per cent
Fair profit ratio	11 per cent
Making a total of	23 per cent

On this as a basis I have made an examination into the reports of one or two of the lighting companies and taking their own figures as regards the cost of the plant, including real estate, one-half of which has been charged against the plant—steam plant, electric plant, electric lines including transformers, meters and arc lamps, and have charged 23 per cent against these. I have taken the operating expenses including station, distribution and management. I have taken the income as given in this report, which undoubtedly includes not only the income from the sale of current, but other sources of income. I have also taken into account the total kilowatt hours generated as given in the report, and the total kilowatt hours sold. From these figures we discover that this Company has received for total kilowatt hours generated, remuneration at the rate of 4.7 cents per kw-hr. They have received per kw-hr. sold, 6.6 cents.

Their expenses have been:

Operating, including distribution and management per kw-hr. generated	2.5	cents
Per kw-hr. sold	3.5	cents
On their fixed charges, the cost of kw-hr. generated is	4.7	cents
Per kw-hr. sold	6.5	cents
Making the total cost of their power per kw-hr. generated	7.3	cents
Per kw-hr. sold	10.0	cents

Evidently then, the central station or this particular central station is operating as a philanthropic enterprise, furnishing power purely for the love of it, because it is quite evident from these figures they are operating at a loss. Nevertheless the stock of this central station stands at a very high figure in the market, and the company is paying large dividends. Evidently they do not use the same basis of figuring as Mr. Parker would have the sales agent of the company use when figuring the cost of power for any industrial enterprise.

I would like to ask, therefore, the central station argument for charging by one method against the central station, and by another method against the industrial plant.

Mr. Kelley: Mr. Hibner states, in regard to power used, "Nearly all of them will tell you that their load is absolutely constant." Another point that they will tell you, if you are seeking to obtain data for a power estimate of their requirements, is that their machinery runs very steadily. I recall one instance where it was necessary to estimate as closely as possible on the probable requirements of the customer in order to conclude a contract. From my own data I took the power required for the machinery, and I went to the proprietor for information as to the time the different classes of machinery had been in operation. Taking that data and working it out I found my power cost was very much higher than I knew it should be in that plant, and by putting a man in that plant with a stop watch on each class of

machinery for two days I found that in some instances the time he had given was actually four times the actual time that machinery was in operation. To give you the conclusion of that affair, the contract was made by the central station with the party on these terms: that the estimated power consumption, if he allowed the central station to place his motors and to make the installation themselves, would be about $50 a month. The central station would put in the plant at its own expense, let him run it a year, paying the bills rendered, and if he was not satisfied at the end of the year would take out the plant at no expense to him except for the power taken. I recollect that the average of the first six months was $47.75 that was paid for the plant at that time. It illustrates the accuracy with which the cost of operating an industrial plant can be predetermined if the factors are all given proper value.

In regard to the statement given in the paper, the difference in cost, or reduction of cost, by a differing use of steam in a steam plant. I can give you the results of power cost estimates that have recently come under my observation. In one case it was that of a plant operating about 1,000 lights and 55 h.p. in motors. The plant used current both for light and power, and mechanical use of steam, for the 24 hr., of course in varying quantities.

The plant consisted of one 125-h.p. engine, 275 rev. per min., direct coupled to a 75-kw. generator, and a 40-h.p. engine direct coupled to a 25-kw. generator. The total of costs for the year, including all the items that have been included in these estimates previously given, was 2.022 cents per kw-hr. That is rather a surprising cost, and it is simply due to the 24-hr. operation and the large use of steam, which reduced the power cost materially over what it would have been if this mechanical use of steam had not existed. That illustrates the fact that almost every industrial plant must be valuated on its own basis; you can't use averages.

For another plant the data is roughly as follows: the total power required was about 1,000 h.p. The water power available varied from 200 h.p. to 400 h.p. and the difference in the amount of industrial power demanded during different seasons of the year ranged as high as 200 h.p., this making a possible maximum variation of about 400 h.p. These conditions were looked into by a central station that desired to provide power. The proposed installation called for a maximum of 500 kw., with an average yearly power of 380 kw., and the price named was something under $30 per h.p., without stating where the power was to be measured. The cost of that plant as it was operating at the time the data was taken was about $27.50 per i.h.p. With a plant laid out aggregating about 790-h.p. in motors, there being 91 in number, and the steam plant re-organized on the basis of the most economical operation, the cost figured out 1.485 cents per kw-hr. The items covered in that estimate are

coal, labor, miscellaneous, supplies, oil, removal of ashes, repairs, interest, the amortization, insurance—both regular boiler insurance and liability insurance—taxes, charges on three months supply of coal, and the charge for supervision.

Another plant had some 500 h.p.—I think exactly 523 h.p.—in motors installed. The company was buying power. It was at the same time operating 500-h.p. in boilers, and supposed it was using steam economically for mechanical purposes for an engine of 75-h.p. and various pumps. Their annual bill for light and power was something over $13,000. By a proper installation on its own premises it reduced the cost of power from $2\frac{1}{2}$ cents per kw-hr. to one cent a kw-hr.

So you can see that every plant must be valuated, upon its own conditions, and all conditions must be taken into account.

John West: The question upon which Mr. Hibner has based his paper, " The Cost of Industrial Power " is " Shall I purchase my power from a power company, or are my conditions such that I can produce it cheaper myself." Mr. Hibner has answered this question by a very accurate estimate of the additional cost for power in the operation of the proposed steam plant. I think, however, that those industrial power engineers who are employed by central stations will agree that the marginal difference between the cost for central station electric power and the cost of manufacturing power in a private plant is in many instances very slight. The facts that live steam for industrial heating, large demands for factory lighting, and the use of factory residue for fuel, enter largely into many industrial power propositions make such conditions typical of the average problem; and to what extent these items will affect the cost of producing power is dependent entirely upon many conditions, as Mr. Hibner has pointed out. This does not mean, however, that the central station industrial power engineer is justified in abandoning his efforts to obtain power business when such conditions are encountered and the engineering data obtained proves discouraging.

It has been proven beyond a doubt that through the use of central station electric power service, certain economies are effected the value of which should be taken into consideration and used to offset the conditions which would seem to prohibit the use of central station power.

While we are considering the manufacturers' lack of technical knowledge and his inability to determine the cost of industrial power it should be remembered that the majority of manufacturers look at the cost of power from the standpoint of its relation to the total cost of production, and for the sake of convenience usually combine light, power and heat to one account. Their figures may be in error from an engineering standpoint, but the fact remains that if a manufacturer considers that his plant investment has paid for itself, and if his credit standing is such that funds are available to the amount necessary to replace his equipment, it is likely to require conclusive proof of the

benefits which he will derive from central station power service in order to obtain his business. Therefore, it is my personal opinion that industrial power engineers engaged in central station work should regard the cost of power from as near the manufacturer's point of view as it is possible to do, and base their arguments upon the economy which central station power represents.

The highest possible price for central station power service should be the result of industrial power engineering; and the true cost of power would seem to be a relative factor in which the value of the service should be considered.

In order to show the value of central station service it is sometimes necessary to make comparisons of economy between manufacturers who are competing in local markets, and the value of such comparisons is of course confined to local application. I have in mind the operation of two manufacturing concerns. Their methods of operation are almost identical and each believes that his operation has approached its highest efficiency. One of these manufacturers has a steam power plant located in the basement of his factory from which steam for heating and manufacturing purposes is supplied and power transmitted to the machinery by mechanical drive. Factory lighting is supplied from a generator which is driven from the engine. The rate capacity of this plant would be 150 kw., and it is being operated at very near full capacity. The other manufacturer employs central station service for power and lighting and maintains a heating plant for factory and industrial heating. A large part of the exhaust steam in the private plant is used for heating, factory residue represents a large portion of the fuel, and the cost of industrial power and light is reduced to a very low figure. In contrast with this figure the rate which the electric company received from the other manufacturer for power and light is high.

Such a comparison would seem to indicate that the private steam plant is the better proposition. By a careful investigation of the gross yearly valuation of the product of each factory and an adjustment of the quality of the products to the cost for power, heat and light it may be shown that the total cost of these three items would represent approximately one-half of 1 per cent of the gross valuation of the product in either case. This bears out the assumption that the cost for industrial power whether obtained from a central station or manufactured in a private power plant will result in approximately the same economy for similar conditions of operation. In this particular instance it becomes necessary to employ some such method of presenting the cost equalizing advantages to be derived from central station service in order to prevent the loss of the business of this central station customer and his neighbors and to forestall the installation of a suggested private steam electric plant to supply light, heat and power for the several manufacturing plants that come in the legal limits.

In reducing the cost of power to an economy basis the chances for error are of course increased, but from a commercial standpoint my experience leads me to believe that the human element enters at this point, and its attitude which has resulted, according to Mr. Hibner's explanation, from ignorance of technical detail, and the desire to reduce the cost of production may be turned to the advantage of the central station power service without misrepresentation of facts.

Mr. Lundgaard has stated in his discussion that Mr. Hibner's paper has been very clear in defining the various factors and really does not leave much to be said when the discussion is limited only to cost. I quite agree with him in that Mr. Hibner has accurately qualified his assumption.

I think however that while, with reference to geographical location, the example he has chosen may be " a typical example of the conditions ordinarily found," it rather serves to exemplify an excellent opportunity for the installation of central station service, than to typify the general average industrial power problem. A commercial load factor of 80 per cent is not unusual for 10-hr. operation in shoe factories but is not generally found when a period of 3000-hr. is considered. The relation of power cost to power value is unnecessary from the central station viewpoint in this example, but if we admit that central station power service would result in an increased production over the use of similar service from a private steam electric plant we are able to arrive at some interesting results. I have assumed that the increased production in this case would amount to 1 per cent for an equal amount of energy consumed. If the gross yearly valuation of the product of the Toronto shoe factory would amount to $1,000,000 and the net profits 25 per cent then this 1 per cent increase in production amounts to $2,500 which has the effect of reducing the cost of power 45.4 per cent. It is not unreasonable to suppose that such advantages as the use of the elevators during the noon hour and for overtime work to facilitate shipment of product and the convenient handling of materials, and the security afforded against shut-downs which will enable the safe working capacity to be increased, together with the continuous coöperation of central station engineers in effecting the highest efficiency of application would result in this increase of production.

If we disregard those advantages which are distinctively inherent to central station power service and which may be said to result in a better quality of power than it is possible to obtain from any other source, we are sure to weaken the position of central station power. We would not seem to be doing full justice to the subject of the cost of industrial power if we excluded the value of quality; and without a standard of economy upon which to base our comparisons of costs I feel safe in the assertion that much power business will be lost to central stations.

C. A. Adams: These papers are very interesting from several points of view. They are encouraging in that they are frank and earnest efforts to reduce to a more rational and scientific basis the computation of the real cost of power; but, when coupled with the discussion, they are very discouraging in that the opinions expressed by various speakers of broad experience and high standing in the profession differ so astoundingly on the vital point at issue, and almost always in the direction of the economic interests of the speaker; in other words it is an illustration of the old theory of economic determinism. It would seem that of all men, engineers from their experience in close contact with the unchangeable laws of nature should be able to see such problems apart from their commercial interest.

Referring now more specifically to the papers, Mr. Hibner appears to have neglected one consideration which may be of considerable import. When considering the cost of power it is very important to know how much of the exhaust steam is used for heating or for industrial purposes and how much of it is wasted; but to this end it is not sufficient to know the relative monthly or daily demand of steam for power and other purposes, since it is quite possible that where the demand for industrial steam during the regular working day considerably exceeds the demand for power steam during the same period, some of the exhaust steam may, nevertheless, be wasted owing to the lack of coincidence of the peaks of the demand curves for industrial and power steam. I know of plants where this is actually the case and where it means an appreciable increase in the real cost of power.

Turn now to the question of profit and the marginal principle referred to in Mr. Parker's paper. The principle involved and its application to the commutation of the cost of power is unassailable, but the opinion as to a fair profit (11 per cent) over and above the 6 per cent interest is one with which I cannot agree. The assumption that the average promotor or investor is not attracted by less than 17 per cent return on his investment is somewhat astounding to those who consider themselves mighty lucky to get 6 per cent. If central stations earn 17 per cent, which I do not believe, it is no wonder that we have so much agitation for public ownership.

Moreover if the promotor or owner of a plant stops his investment when the marginal investment ceases to earn 17 per cent, it is to be assumed that he can place any additional capital he may have at that figure. Why then should not the amount set aside for amortization be earning 17 per cent rather than 6 per cent which is considered too high by many.

Since the profit ratio is a quantity concerning which there is a wide difference of opinion, and since the 6 per cent interest is fairly well agreed upon, would it not be better to exclude the profit from the fixed charges in figuring cost of power. This would reduce power-cost to a parity with the cost of other

things,—what we have to pay for them. Then the profit in the manufacture of power could be figured for each case, and if it fell below the desired point, the proposition would be discarded as not yielding enough profit. The result is obviously the same, but the method here proposed would eliminate a large amount of unnecessary and profitless discussion.

I have here some figures on the cost of power in a particular plant which may be of interest. It is the case of an industrial establishment where the total amount of steam consumed is vastly in excess of the amount required for power, and where all the exhaust steam is utilized. Including even the 17 per cent (6 per cent interest and 11 per cent profit) fixed charge in addition to insurance, taxes and amortization, the total cost of power per kilowatt hour is only 9/10 of a cent; and without the profit, simply charging 6 per cent interest on the money, the actual cost of power comes to about 56/100 of a cent a kilowatt hour. These are not figures concerning which there is any doubt, everything has been allowed for. The reason for the low cost is that the plant runs 144 hours per week at a load factor of at least 80 per cent and all of the exhaust steam is used for industrial purposes.

N. T. Wilcox: What is the price of coal?

C. A. Adams: The price of coal is $2.20 and the plant is on tide water.

J. F. Vaughan: Referring to Mr. Adams' discussion of fixed charges, it is common in new enterprises to divide the interest item into two parts; one, straight interest for raising the money, and the other a certain percentage for covering the risk of investment. It would seem reasonable in comparing a central station with some isolated plant to allow the same percentage for covering the "reasonable risk" in each case. In a going system, however, allowance for such risk is not justified except in cases of considerable extension or a development of new business.

There is one point that I should like to refer to in Mr. Dudley's discussion at Toronto, of Mr. Hibner's paper, and that is the ambiguity of the term "horse power year" as ordinarily used. He brings out clearly that this term means nothing unless the load factor is stated. He gives some interesting data on this question of load factor in manufacturing plants of various kinds; for instance, the load factor for cement mills is given as 85 per cent, textile mills, cotton mills, etc., 75 per cent to 90 per cent, and so on.

C. A. Adams: They are 10-hr. load factors, are they not?

J. F. Vaughan: They appear to be 10-hr. load factors.

Mr. Cook: I would say that one of the points to be considered is whether it is 10-h.p. or 10,000 h.p. and these figures that Professor Adams presented don't mean very much to me unless we know how large the plant is.

C. A. Adams: 1000 h.p.

Thomas M. Roberts: I should like to put one of the first sentences of Mr. Parker's paper with one of the final sentences of Mr. Hibner's. Mr. Parker speaks in regard to the fixed costs being determined somewhat by the *first layout*, and Mr. Hibner's paper in the final sentence in regard to the time in the future when no factory will be without its *consulting engineer*. I have just recently had occasion to visit one of the large mills of New England, and the agent for the mill being one of the shrewdest business men, probably, in New England, and he sees immediately where advantage is gained by putting capital into the right investment to improve his electrical equipment for his mills. When it is pointed out that although an underground system will cost more than twice as much as a pole line system to distribute the power of the mills he immediately sees the advantage of that underground system, in that the cables can be put closer together, less copper is involved in carrying the power some 1,000 or 1,500 ft., and the maintenance of the underground system when once installed is very small, in fact it is there to eternity, relatively speaking, by the side of other apparatus; and he sees in figuring up his coal bill that in the course of a year on something like $60,000 worth of coal he can gain $\frac{3}{4}$ of 1 per cent, say, on the investment, by putting things underground instead of overhead. Well, that is a margin, and it is worth financiers' notice.

The cost of copper now is low; we don't know what is liable to happen. It is liable to go back to where it was a few years ago, up to 20 cents a pound. And yet the first cost of apparatus in transmission is a very decided factor in the problem here, although this paper does not discuss that end of it. It seems to me that the first installation, properly installed, means a very marked factor in the fixed costs on the coal bill. I have come across many cases where a plant is already installed and a manager wants to supplement it with new motors, he will say, "Here, we have running through the mill so many circular mils of copper and it is not half loaded yet according to the insurance rules." Well, when we come to figure out the amount of copper he has, and the voltage drop, if it is alternating current (the reactance factor running perhaps nearly three times as much as the resistance factor), we find unless he adds considerably more copper he will not get the right voltage delivered to the motors. That brings up the question of voltage, or the main factor in transmission. A large portion of the mills throughout New England are based on 600 volts at the switchboard and 550 at the motors, yet there are quite a number that are not afraid of 2300. It means not only fulfilling insurance rules, but it means a decidedly less first cost on the copper; it means a decidedly less $I^2 R$ loss, which is continually eating up the coal bill; and the time may come, (and I feel quite confident personally that it will come), when 6,600 will be delivered into the mills instead of 600 or 2300. It is simply a matter of educating the general engineering public,

and especially the fire insurance people, to the fact that it is no more dangerous, so far as the risk is concerned, when properly installed, than the lower voltages.

It seems to me, as engineers, we cannot dodge this question of getting the power from the centre to the consumers, or to the receiving units at low cost; and that it is poor economy for a consulting engineer in laying out a plant to put the power house down by the water unless he can balance up against it the additional cost of transmitting the energy to the center. Let me put that another way. Let us suppose that the central power station, at the mills, is near the water, and it is also at one end of the mills. Now, the consulting engineer must balance up the advantage of being near the water for condensing purposes and delivery of coal, against the added cost of transmitting the energy, say several hundred or a thousand feet, as the case may be, to the farthest mills; while if he puts the plant in the center of distribution and carries his coal a little farther, and first puts up the price of an extra circulating pump, or something of that sort, in his auxiliaries, he may find—and certainly putting the costs side by side he will find—that it is better in the end to put his power station in the center of distribution rather than down by the water to save the cost of a circulating pump. To me these factors are coming up continually in meeting the extension equipments and new equipments in New England mills, and it seems to me are overlooked very largely by the manufacturers themselves.

F. M. Gunby: The cost of power has been discussed to quite an extent, both as to the gross and net costs. But the cases sighted, in which part of the by-products of the steam plant were used for heating and manufacturing, were confined mostly to plants in which heating only was required.

I wish to say something about the credits to the cost of power in plants where more of the by-products of the steam plant are made use of. The net cost of power to a manufacturing concern is the gross cost of power minus the costs of all of the waste products which are made use of in the manufacturing process.

These remarks refer principally to plants of fair sizes, such as might be found in textile mills. By fair sizes, we mean 500 or 1000 kw. and upwards. I will refer below to "bleeding" steam, by which I mean steam which is taken from between the cylinders of a compound engine or from between the stages, or parts corresponding to stages, in turbines.

Mr. Charles T. Main stated in his paper entitled "Choice of Power for Textile Mills," read before the National Association of Cotton Manufacturers in 1910, that the gross cost of power might be reduced by the amounts given in the table below by the use of steam bled in the manner described. This table was made up originally to apply to steam engines, but is also practically applicable to turbines with slight modifications:

Per cent of steam used (bled)	Coal at $5 per long ton per kilowatt year	Coal at $4 per long ton per kilowatt year
25	$3.00 to $4 00	$2.40 to $3.20
50	6.00 " 8.00	4.80 " 6 40
75	9 50 " 12.00	7.60 " 9.60
100	12 50 " 16.00	10.00 " 12.00 .

We recently had occasion to analyze the cost of power of a plant which was in operation, where a considerable part of the hot water from the condenser was used in the dye house and about 30 per cent of the steam to the high pressure cylinder was taken out at the receiver and used for heating the buildings in winter. This analysis was made by conducting several tests on the plant and also by obtaining information from the station reports and mill books. In this case the gross cost of power was reduced, due to the credits for heat units used in manufacturing by about 23 per cent.

In some plants it is possible to greatly increase these credits by bleeding more steam or even by running non-condensing. In this particular plant to introduce these further refinements would have led to two systems of steam piping in the dye house, as only part of the processes could use exhaust steam, and also it was found that the help in this particular plant were accustomed to using high pressure steam in their machines. Any oil in the manufacturing steam was also objectionable and at the time that the plant was installed, the bleeding of turbines was unfavorably regarded by the turbine builders.

It is interesting to note in connection with the operation of this plant that twelve boilers are run daily, while the steam going to the engine requires the output of only two boilers.

Another manufacturing plant of the same type as the above, where the mill help is accustomed to the use of low pressure steam, is installing a turbine plant where about one-half of the steam power will be obtained from non-condensing turbines and turbines from which steam may be bled. The rest of the steam power will be obtained from condensing turbines, thus giving a very flexible arrangement. Part of the hot water from the condensing machines will be used for manufacturing processes.

Credits to power in this plant will be a great deal more than the above. The actual cost of coal for power will be represented by the work done and the losses in the turbines and piping to and from them, and in such warm water as goes to waste.

While the proportion of the turbines installed in the past which have steam bled from them is not nearly so great as that of the engines, in this section, it would seem that bleeding turbines should prove to have greater advantages than bleeding engines.

1. Because there is probably less B.t.u. loss, due to condensation in a turbine than in an engine.

2. Because the steam bled from a turbine is free from oil, which might soil the manufactured product. This, of course, is not the case with an engine on account of the cylinder oil.

It is very gratifying to see that the turbine builders are coming to realize these facts and are modifying their designs to facilitate this bleeding.

J. C. Parker: The discussion has been so extensive that it does not seem that the author could add anything in closing except to emphasize and possibly explain some of the points on which differences of opinion have arisen.

These very differences of opinion have been a source of disquietude to one of the speakers. To the author, however, it is rather satisfactory to note that these differences have arisen, since they have at the least indicated that the paper does not deal with a subject on which there is so great unanimity as to make a discussion unprofitable, nor does the author feel that these differences are surprising. Human knowledge is always increased by going from the things that we know intimately to the things that are less familiar and in the process there is always a similarity to or differentiation from the things that we have believed in the past, so that it is not surprising that Mr. Moses, whose work has been in one field; Mr. Williams, whose work is in the same field as the author's but in a different locality, and the author, should arrive at somewhat different conclusions as to different data. The author is sure that as we all progress in knowledge, we will come together more and more closely, approaching the limit from many different directions.

It does not seem worth while to discuss in detail the numerical data presented by the various gentlemen who have contributed to the discussion. It is all interesting and valuable when weighed with relation to the point of attack and the inevitable predisposition which in even abstractly scientific work subconsciously influences the observer. That the author's own data is influenced by such considerations he would not for a moment attempt to deny but he is not sure as to the side on which he errs. In the attempt to make the data conservative he would be influenced to find low first cost and low operating cost, while on the other hand, were the wish father to the thought, he would naturally believe that both investment and operating costs are very high.

He does believe, however, that estimates based upon operation over a period of years are more conclusive than test data gathered from a ten or twenty-four hour test when firemen and enginemen are naturally endeavoring to make as good a showing as possible for the plant, and during which it is very hard to accurately determine banking coal and impossible to ascertain supplies, repairs, etc. Similarly it is almost impossible to make an estimate of the first cost of a plant from an addition of the constituent items, in which even a skilled engineer may readily fail to incorporate a mass of small but, in the aggregate

expensive details entering into the plant. In so many cases has the author found the actual facts to be widely variant from pre-estimates and from short period test data that he is forced regretfully to confess the inadequacy of such methods.

The author would like to direct attention again to the fact that, while apparently high, all the installation figures given in his paper are from actual quotation and the operating costs are based on observation of a very large number of plants actually run for a period of years. In connection with the latter it should be noted that adequate book-keeping is distinctly the exception rather than the rule and that where bookkeeping has been accurately carried out, the cost of repairs, etc., is invariably shown to be much higher than where the usual and slipshod methods have been pursued.

Considerable discussion has attached to the operation of the marginal principal with reference to both managerial time and fixed investment.

While it may betoken bad management, the author's observation has been that, whether they should or not, managers give a very great amount of time to the operation of their engine plants. It may be that this in part arises from the eternal boy in even the most serious minded adults, and it may be that an able man could not be employed on even an ample salary to devote his life to the supervision of 200 or 300 h.p. of apparatus.

That such time should be charged with only its fair salary value seems to the author a fallacious contention. He does not believe that the owner of an establishment would employ a $10,000 manager unless the owner expected to make or to save two or three times that amount as a justification for employing him, and it certainly involves a loss of whatever would have been gained when such a manager's time is diverted to other activities without producing such a gain.

The same reasoning applies to capital invested. Many a time has every business man expressed himself by saying that he cannot afford to put money into a certain venture because he will make so much more by putting it into the venture which he already has. The same reasoning must apply to the details within the business.

Some of the gentlemen discussing the paper have evidently misapprehended the operation of the margin in that they have claimed that there are very few businesses that would pay as big a profit as the author has assessed against an isolated plant. This is perfectly true and applies to the central station business as well as to the industrial and mercantile pursuits. A study of the curve given in the paper will indicate that certain essential factors in the business are, as brought out by Mr. Peck, non-productive and must, whether one will or no, be taken at a loss in order to put the owner in a position where he can discharge the ultimate functions of the business. As shown by the curve, such features reduce the average profit perhaps much

below that obtaining at the margin, which is in itself a constantly decreasing amount.

Reference has been made to the fair profit for the central station. The author agrees with several of the speakers, that assuming an *average* profit of 11 per cent, almost every central station in the country would appear as a charitable institution, but after noting that the average profit is very much lower than the marginal profit we may note one other fact; namely, that the margin of profit is determined by the individual and by the business and is different for different individuals and different industries, being always defined, as noted in the paper, as the most that can be got in any other business of which the promoter has knowledge. The public utilities art being practically a standardized and assured one with relatively small local competition, the proprietors suffer less risk of total failure than do the proprietors of an industry that may be more or less new and untried and where local or outside competition, operating through the channel of transportation and changes in the public whim, may at any time precipitate financial disaster. This fact is illustrated by a reference to the conditions obtaining in stock exchange quotations of industrials and of railroad securities.

That the amortization fund should not bear interest at the normal interest rate plus the fair profit rate seems to the author to be an entirely correct proposition, since while the amortization fund may be reinvested in the business, it is simply a case of the firm borrowing money for the business from its own amortization fund at the market rate, and while such borrowings may and properly should pay the same fair profit as any other borrowed money, this extra earning is properly creditable to the business as an inducement for borrowing and investment.

Aldis E. Hibner: In concluding the discussion which has been so valuable in demonstrating the different view points of those dealing with industrial power costs, I wish merely to explain my own point of view more fully where it seems to have been misunderstood by the various speakers.

In the first place, mention has been made concerning the selection of an 80 per cent load factor. It is obvious that some basis for calculation must be assumed and this value was selected as fitting the case of a shoe factory from which my example was derived. As pointed out, this is higher than can ordinarily be obtained and for that reason a curve was plotted in Fig. 3 giving the cost of power for any other load factor.

Mr. Arthur Williams in his discussion has assumed that the heating load was 62 h.p. If reference is made to Fig. 1 it will be seen that the average heating load is 44 h.p. As to the amount of coal required for heating, the conditions vary so enormously that each problem requires special treatment. For the particular case the writer had in mind in his example 475 tons for the heating season is not excessive. The object of charging full time for a fireman for heating the building is given in the

paper. We can only charge against the cost of power the actual additional expense incurred by its generation.

The example of power costs from fifteen plants given by Mr. John H. Norris might be of considerable value if given more in details. As the figures stand at present, however, they are of little value as in numerous instances the price of the fuel is not given. In the case of Plant No. 12 the fuel cost is taken at 0.3 cent per kw-hr. whereas the results of the tests given in the plant show a fuel cost of 0.47 cent in one case and 0.69 cent in the other.

Also in the case of Plant 15 the cost of fuel is taken at 0.17 cent in one place whereas in the results of the test in this plant the fuel cost is given at 0.42 cent. Furthermore, only 10 per cent is figured to cover the fixed cost of a gas engine plant and this should, in the writer's opinion, be raised to at least 15 per cent.

In answer to Mr. Tillman's question regarding the items of coal for night heating and for banking, I would say that the coal for night heating is the additional amount required for heating the building during the winter months over and above what would be required for simply banking the boilers over night.

In conclusion I wish to emphasize what Mr. Jackson has said regarding the imperative demand for detailed figures in comparing power costs. Much data that would be very valuable is made worthless by lack of detail on points of vital importance.

A paper presented at the Milwaukee Section of the American Institute of Electrical Engineers, Milwaukee, Wis., April 12, 1911.

FLYWHEEL LOAD EQUALIZER

BY W. N. MOTTER AND L. L. TATUM

The use of flywheels to equalize the loads on steam engines, punch presses, rolling mills and other machinery of this class has been known for years but its use in connection with electrical machinery for operating hoists, steel rolls, etc., is comparatively new.

Peak loads of relatively long duration are universally handled either direct by the generating equipment or with the assistance of storage batteries, but for conditions where the peak load is of short duration, the flywheel equalizer is cheaper, more efficient and better suited.

For short peak loads, such as are met with on rolls, punches, planers, etc., where non-reversible motors are used, the flywheels are direct-driven by the motor on which the load comes, and the flywheel transforms only the energy of the peaks. Where the driving motor must be reversible, such as in steel mills, electrical hoists, etc., the flywheel is necessarily carried by some other device, usually a motor-generator which acts as a link in the transmission system, and whether the supply be direct or alternating current, the energy is all transformed from electrical to mechanical, and from mechanical back again to electrical.

It is the purpose of this paper to give data from an installation now in operation, which is a typical example of conditions existing in many parts of the country where reversible motors are used, and in which a flywheel may be used to transform the energy of the peaks only. The installation used as an example is an ore hoisting equipment. The load to be handled consists of three ore bridges, each equipped with three 125-h.p., one 75-h.p., and one 5-h.p., 500-volt motors, aggregating 1365 h.p.

The capacity of these hoists is 10,000 tons of ore in ten hours. The power is obtained from the feeders of a 550-volt trolley system some 1,100 ft. (335 m.) from the generating station.

Graphical records taken to determine the number and size of peak loads in a certain given time showed the following results:

Record No. 1. Highest peak 1,200 amperes for ten seconds; about one peak of 1000 amperes every five minutes. Most peaks average 600 amperes.

Record No. 2. Highest peak 1,400 amperes; about one peak reaching 1,100 to 1,200 amperes every five minutes. Average peak about 850 amperes.

Record No. 3. Maximum peak 1,600 amperes, other peaks of 1,400 amperes about once every 15 minutes, most of the peaks not exceeding 800 amperes.

Record No. 4. Maximum peak 1000 amperes, most peaks not exceeding 700 amperes.

The ratio of average amperes to maximum amperes ranges from 17 to 25 per cent and the maximum kilowatt demand is 880. When unloading wet ore this ratio is reduced and the maximum demand naturally increased, the loads being sufficient at many times to open a circuit breaker which was set at 2000 amperes.

Analysis of the above records show a recorded maximum load of 1600 amperes, while the tripping of the circuit breaker when handling wet ore shows 2000 amperes, or 1,100 kw. These peaks were necessarily considered in determining the demand charge for service, but inspection of the record indicated an average load of only 300 to 400 amperes, with a maximum of 600 amperes, or 330 kw., if the short peaks could be eliminated or absorbed.

The problem then was to obtain a method of keeping the peak loads down to 600 amperes and thereby obtain a maximum demand charge on this basis. To secure this reduction, three methods were offered, namely, a storage battery, motor-generator sets, and an idle motor with flywheel floating on the 550-volt line.

Taking the cost, weight, and floor space of the idle motor equipment as unity, the storage battery proposition would cost initially 3.9 to 4.6 depending on type of regulation. The maintenance of the battery would be higher than would be expected either of the motor-generator set or the floating flywheel motor set. Of course, the battery in itself would be free from moving parts, but a booster would be necessary in connection with it.

Again, it would be necessary for this booster to respond only in proportion to the change in amperes required by the hoists and be unresponsive to variation in the railway load which is on the same feeder. The battery would, however, transform only the peak loads, the average being carried directly by the feeder. The efficiency of the double transformation, including the booster losses, was estimated at not over 66 per cent.

The motor-generator set of 2,000 amperes, or 1100 kw., peak loads would cost on the above basis about 1.13. The weight, including the flywheel, would be about 1.5, and the efficiency at 2,000 amperes would be about 81 per cent. Under normal conditions, with a load of zero to 1000 amperes, averaging 300 amperes, the efficiency of the set would approximate 72 per cent, or a constant running loss of 65 kw. The regulation of the set would be excellent, using a compound-wound motor and compound-wound generator, and would require no auxiliary apparatus to secure this regulation. It would not have any great tendency to assume any part of the railroad load.

The third proposition, namely, the motor with a flywheel floating on the line would cost 1. The function of this machine would be quite similar to that of the storage battery in that it would furnish the energy for the peak loads and there would be no transformation of the normal energy absorbed by the hoist motors. The constant running loss would be about 38 kw., or for an average load of 300 amperes, an efficiency of 80 per cent.

This form offered advantages over the battery of lower first cost, higher efficiency, lower depreciation, greater simplicity of regulation and less floor space. Over the motor-generator it offered the advantages of lower first cost, higher efficiency and less weight and floor space. It was, therefore, decided to install a motor with a flywheel floating on the line, and specifications were drawn up requiring that no more than 600 amperes be drawn from the line when a peak load of 2000 amperes was delivered to the hoist. This meant that the flywheel must be of such capacity as to deliver 1,400 amperes at 550 volts for 15 seconds.

The apparatus installed consisted of an interpole motor of 300-kw., 550-volt, 600-rev. per min. rating for normal capacity, with an over-load capacity of 850 kw. for 15 seconds, with a drop in speed of 22 per cent. The flywheel was a solid cast steel disk nine ft. (2.7 m.) in diameter by 15½ in. (39.3 cm.) face.

The armature and rotating parts weigh 47,275 lb. (21,442 kg.),

which at 600 rev. per min., represents 25,700,000 ft-lb. of energy stored. (ft-lb. = kg-m. × 7.233). At 470 rev. per min. the energy stored equals 16,000,000 ft-lb., or with a 22 per cent drop in speed there would be delivered 9,700,000 ft-lb. of energy. If this change in speed took place in 15 seconds, the energy delivered would be 875 kw. or 1600 amperes at 550 volt, or more than the maximum peak required, as shown by the original records.

Fig. 1 shows the flywheel generator set as installed. The flywheel was housed in a sheet steel casing to prevent accident and to reduce the windage loss. This windage loss even on a smooth surface becomes a factor when a peripheral speed of

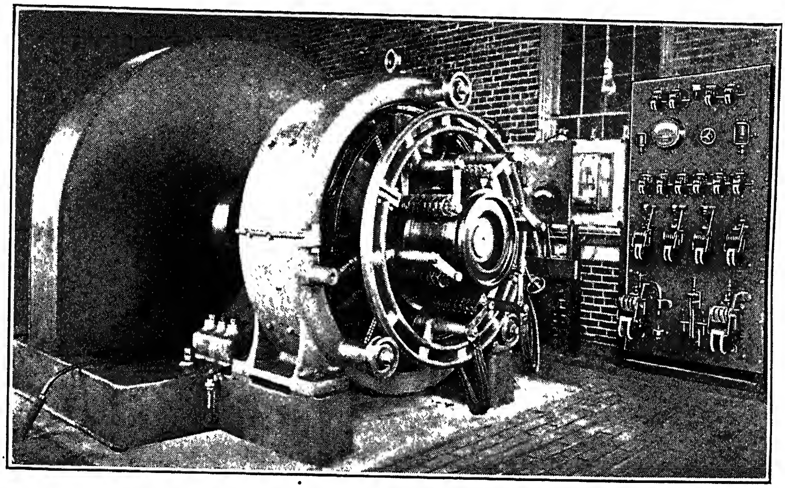


FIG. 1.—Flywheel generator set

17,000 ft. (5181 m.) per minute is reached. The reduction in windage loss, due to the cover being on, amounted to 2.1 kw.

Fig. 2 is a schematic diagram of the main electrical connections. The motor was compound-wound, the series winding being on the load side of the circuit between the hoist and the motor. This allowed operation as a shunt motor when the flywheel was taking energy from the feeder, but when delivering energy to the hoists the machine acted as a compound-wound generator. Since the hoists took some, or the average, current directly from the feeder, which would, at all times, partially energize the series winding, a magnetic switch $S\ S$ (Fig. 2) was installed to short-circuit it. A current relay, $C\ R$ (Fig. 2) controlled the magnetic

switch opening the short-circuit around the series winding at a hoist current of 400 amperes. At 400 amperes the series winding was suddenly energized and the counter e.m.f. of the machine raised enough to cause it to deliver energy to the circuit, instead of absorbing energy from it. The series winding was so adjusted that the delivered energy was approximately proportional to the current in the series coil, making the machine take the desired proportion of the total load. When the demand dropped to about 300 amperes the series coil was again short-circuited dropping the voltage, so that the flywheel again absorbed energy.

Fig. 2 also shows the shunt field connection scheme. On account of the approximately constant line voltage, and the variable speed, 470 to 615 rev. per min., it was necessary to adjust automatically the shunt field strength to suit the momentary values of the speed. If the field was too weak, the motor

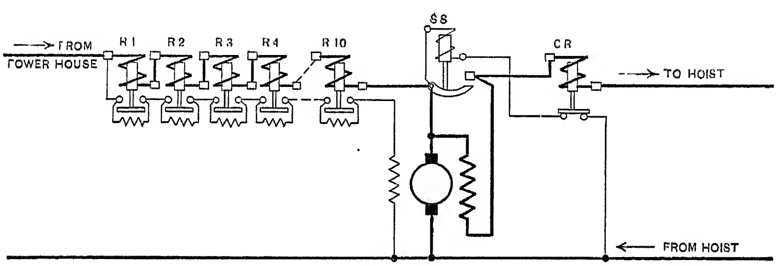


FIG. 2.—Schematic diagram of principal connections

current or rate of absorbing energy would be too high, while if generating, the voltage would be too low to allow the machine to take its proper proportion of the total. Either case would throw heavier loads on the feeder. To correct for this, current relays, R_1 R_2 R_3, etc., (Fig. 2), were connected in the feeder and arranged to commutate resistance in series with the shunt field. These were set to operate at different values, from 400 to 600 amperes. Below 400 amperes, that is, below the average load, all relays were open, and weak field existed, tending to give maximum speed to the flywheel. Above 400 amperes feeder current some relays closed, strengthening the field, and reducing the motor current, or increasing the generated current, depending on whether the series coil was in action or not. Under a sustained peak the flywheel would slow down gradually and the field would strengthen gradually until with the wheel at its

lowest speed, 470 rev. per min., and maximum field strength, the feeder would be supplying 600 amperes.

The function of the shunt field regulation was therefore to maintain the voltage of the flywheel machine approximately equal to the feeder voltage under all conditions of speed, while the auxiliary series field and its switch and relay changed the characteristics from those of a motor to those of a generator as needed.

As part of the control system, a current limiting relay self-started was provided to automatically take care of the necessarily slow start, and several safety features were added. The troubles to be anticipated were overload, overspeed, and pumping back into the feeder in case of lowering or failure of supply voltage. The first two would be local troubles, needing investigation of the attendant before restarting. Overload was cared for by automatically cutting the flywheel machine off the feeders, requiring manual operation of the control switch for resetting. Overspeed was cared for by a centrifugal device on the shaft of the machine opening the circuit the same as an overload, but requiring resetting of the governor as well as the control switch before starting. Pumping back, being due to causes beyond the control of the attendant, was made automatic. A reverse current relay tripped at about 200 amperes reverse current, inserting a resistance to limit the value of the reverse current. On restoration of line voltage, the current would flow in the normal direction, the relay reset, and the flywheel automatically restart, or regain speed.

Fig. 3 is the detail connection diagram of the system.

After the system was installed and adjusted, provisions were made for taking simultaneous graphical meter curves on the feeder and on the load circuits. These curves are shown in Fig. 4. The upper curve, noted as accelerating curve, shows the cycle through which the machine passes when started up. Due to the high voltage the initial surge of the current exceeds the 600 limit slightly, falling off, as the motor accelerates, to 275 amperes after $1\frac{3}{4}$ minutes. The first accelerating switch then closes giving a second surge of 500 amperes. The current then gradually falls for about $1\frac{3}{4}$ minutes when the second switch comes in, etc. It is interesting to note that after the fourth peak the current line becomes wavy due to the voltage fluctuation with but little resistance in the circuit. The fifth peak is caused by the closing of the last switch putting the armature directly on the

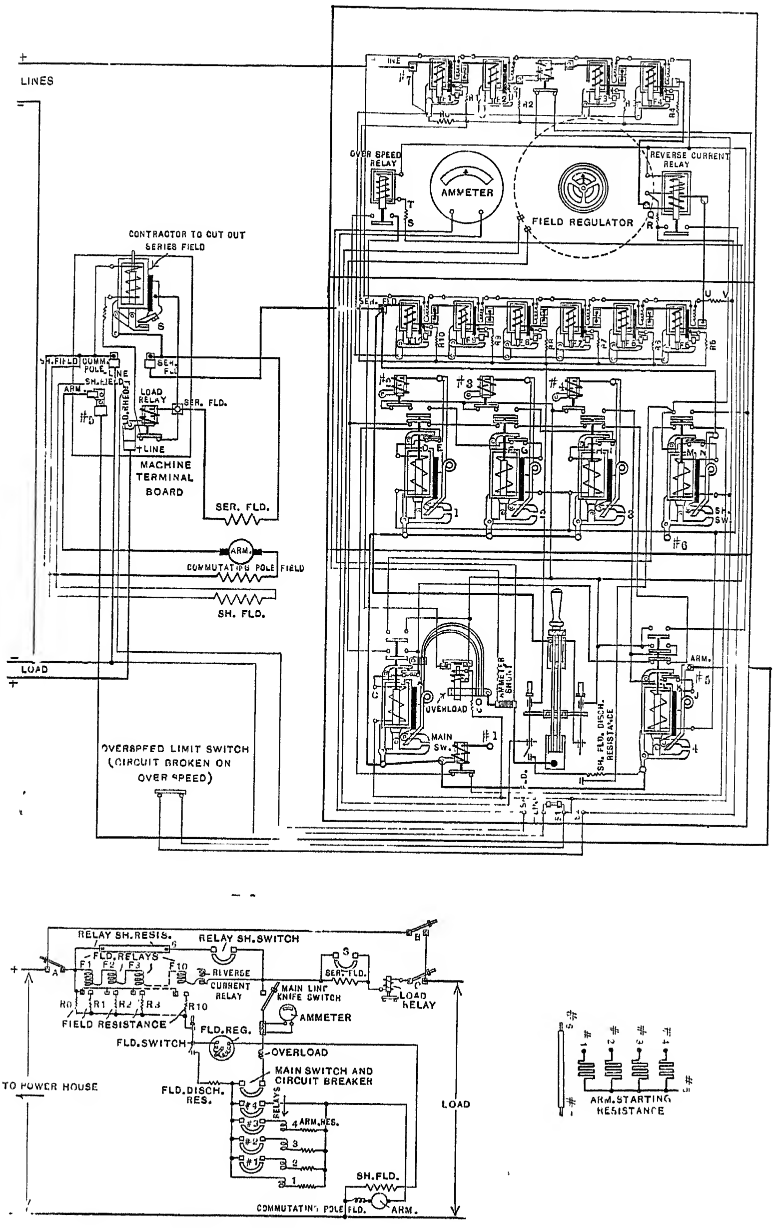


FIG. 3.—Detail connection diagram

line. At this point the speed is 470 rev. per min., which comes after about $4\frac{1}{2}$ minutes. As the current decreases further the line relays come into play, weakening the field for further acceleration. The field relays were maintained closed up to this point, at currents much below their normal settings, by sending the entire current through them, but at $6\frac{1}{2}$ minutes, at a current of 180 amperes, a switch closed shunting half the current from the relays so as to reduce their settings by one half. The large oscillations immediately following show the hunting of these relays while reestablishing equilibrium. The machine had reached its full speed at the end of seven minutes.

A record of $2\frac{1}{2}$ hours duration was made on this machine. The portion shown in Fig. 4 is a typical result of the entire record. The first three minutes were made under normal conditions, that is, the three hoists were operating independent of each other. From the third to the sixteenth minute an attempt was made to get the maximum peak by operating all hoists simultaneously. A maximum of 1600 amperes was obtained in the fifteenth minute and the line current at this point reached 600 amperes, and again reached 600 amperes with a succeeding peak of 1300 amperes. It will be noted, however, that these peaks fall within one minute of each other at the end of a series of excessive peaks, and the speed of the flywheel was much reduced. Correcting for the low speed it was found that there was sufficient energy in the wheel to deliver 2000 amperes to the hoist and not draw more than 600 from the line. From the sixteenth minute on, the operating conditions were again normal, the flywheel having regained its normal speed. During part of the test, not shown on the curves, the machine was run with the series field in circuit constantly. The effect of this was to smooth out the line current curve, but it would not keep the maximum peak loads as low as when the relays were set to cut the series in and out of circuit, due to the added excitation of the series field holding down the maximum speed and thus reducing the stored energy.

The regulation of this set is based on raising its voltage above that of the feeder just enough to take its share of the load, and, as shown, this share varies with the speed, being more at maximum and less at low speed. On the end of a feeder line this variation does no harm, merely shifting a varying proportion to the power house. If, however, the set were installed in the power house with no line drop between the main generators and

the flywheel set, this variation would probably cause the flywheel to take the entire station load at maximum speed, while at minimum speed it might take none. With over-compounded generators this would probably be true, but with a drooping characteristic of the main generators the trouble would be reduced. These conditions, however, make it very doubtful whether successful operation could be obtained with the set installed in, or very close to, the main generating plant. If used with a synchronous converter, which would give the necessary drooping characteristics, such a set could be advantageously used in the power house with alternating-current generators as the main source of supply.

The action of the set has been very satisfactory from a mechanical and electrical standpoint. From a financial point it has also been exceptionally good, as shown by the following table which gives the cost of current and the ore handled by the dock for corresponding months in the last three years. In 1908 the flywheel set was not in operation. In 1909 and 1910 it was used.

	1908			1909			1910		
	Tons	Cost	Per ton	Tons	Cost	Per ton	Tons	Cost	Per ton
Sept......	32336	$820	0.0255	82097	$652	0.0080	67715	$560	0.0083
Oct.......	39900	910	0.0227	96183	592	0.0062	54558	510	0 0094
Nov......	36175	870	0.0240	94614	720	0.0077	35287	480	0.0136

Whether or not the installation of such apparatus is warranted requires a careful study of load peaks as well as rates. Where the definition of "peak" as used in determining rates is a maintained rate for 15 minutes or more, it would be manifestly unwise. In fact, a maintained rate of even 600 amperes for 15 seconds is not shown on the load chart, though an average for 15 seconds would be found much higher than 600 amperes. A five-second peak of 1100 amperes, a three-second peak of 1300 amperes, and a momentary peak of 1600 amperes are found.

As an example, the rates applying around Duluth may be applied to this chart. The demand rate may be based on 40 per cent of a momentary peak, or 50 per cent of a one-minute peak, or $66\frac{2}{3}$ per cent of a three-minute peak, or the net value of a five-minute peak. The 40 per cent momentary value is largest,

and is 640 amperes or 352 kw. The other peaks would all be zero, as at no place on the chart is found a full minute without a zero reading. The demand charge, or reservation charge, is \$1.00 per kw. per month on the maximum rate adjustment above, or \$352 per month. The current charge is made up of two items; seventy hours at demand rate and \$0.0125 per kw. hr., or 24,640 kw-hr. at \$0.0125, or \$308. The balance is at the rate of \$0.006 per kw-hr. On the assumption of 260 hours per month at 250 amperes, or $137\frac{1}{2}$ kw. average, the kilowatt-hours would be 35,750, leaving a balance of 11,110 kw-hr. for which the rate is \$0.006 or \$66.66, making a total of \$726.66.

With the flywheel, the integrated load would be increased to say 300 amperes or 165 kw., or 42,900 kw-hr. The demand would be 40 per cent of 600 amperes or 240, or on a five-minute net rate would be 300 amperes or 165 kw. The latter would, therefore, be the base rate. The demand charge would then be \$165. The first item of charge 165×70 equals 11,550 kw-hr., at \$0.0125 or \$144.37. and the remaining 31,350 kw-hr. at \$0.006 equals \$188.10, or a total of \$497.47, a reduction of approximately \$230 per month. If, however, the hoist stood idle for a month with no current consumption whatever, the presence of the set would mean a reduction in the demand charge from \$352 to \$165, or a saving of \$187.

In cases where the supply is alternating current, direct-current motors can be used with a synchronous converter, and a direct-current flywheel set, with the transformers and converter having only capacity for slightly more than the integrated load, while the flywheel machine has momentary capacity for the difference between that rating and the peaks. Compared to an induction motor-generator the overall efficiency would be 81 percent for the rotary and the flywheel machine, as against 81.5 per cent for the induction motor flywheel set. The power factor would be unity as against about 94 per cent. The cost would be about as one to 1.03 in favor of the converter. The relative weight of the converter and flywheel set to the motor-generator set with a flywheel would be one to 1.13. A storage battery could hardly be considered in this case.

From the foregoing it appears that for short peak loads, especially where the ratio of the peak to the average load is large, the type of installation described is advantageous on account of low first cost, high efficiency, ease of regulation, ease of protection against abnormal conditions, comparatively light weight and small floor space necessary.

A direct-current to direct-current motor-generator flywheel set would have the advantage of simpler regulation, but would cost more, be less efficient, and heavier and bulkier.

A flywheel motor-generator set having an alternating-current motor wound for use without transformers and a direct-current generator compares very favorably with the motor flywheel set with the use of a converter and transformers.

A storage battery would have no point of advantage but would be higher in cost, lower in efficiency, more complicated in regulation, higher in maintenance, heavier and bulkier. In cases where the maximum peaks were of long duration, it would, however, have advantages to more than offset these. It appears also that where the demand charge is based on peaks of more than 15 seconds, there would be nothing gained with a load of the type described, by the installation of any load equalizing device, unless the line losses were so bad as to make the improvement of service warrant the expenditure.

A paper presented at the 261st Meeting of the American Institute of Electrical Engineers, New York, April 14, 1911.

COMMERCIAL TESTING OF SHEET IRON FOR HYSTERESIS LOSS

BY L. T. ROBINSON

The desirability of being able to determine quickly and with reasonable accuracy and cost the hysteresis and eddy losses in sheet iron for use in transformers and other alternating current apparatus is fully appreciated and need not be discussed. The arrangements that have been devised by various workers along this line, some of which have been described,* evince the fact that the subject has received much attention from time to time and that the methods of testing samples by means of ballistic galvanometer or by wattmeter test on complete apparatus are not entirely satisfactory.

The purpose of the present paper is to discuss the question generally in the light of practical requirements of the maker or user of sheets and to describe means which have been devised as a result of many years experience in meeting shop requirements for making the regular tests.

*I. Epstein, *Electrotechniche Zeitschrift*, Vol. 21, No. 16, April 19, 1900, page 303.

E. Gumlich and P. Rose, *Electrotechniche Zeitschrift*, page 403, Vol. 26, No. 17, April 27, 1905.

J. A. Mollinger, *Electrotechniche Zeitschrift* Vol. 22, No. 18, 1901, page 379.

Various abstracts from the Proceedings of the Vereindeutcher Elek trochniker E. T. Z., page 520 No. 20, May 19, 1910; page 740 No. 28, July 13, 1910; page 826, August 11, 1910; page 684, Aug. 20, 1903; page 720, July 27, 1905; page 801, Sept. 19, 1901.

National Bureau of Standards Reprint 109, Testing of Transformer Steel, by Lloyd and Fisher.

Battie Electrician, Vol. 62, page 136, 1908.

J. W. Esterline, Proc. Am. Soc., Testing Materials, Vol. 8, page 190, 1908.

For the purpose of showing the general degree of accuracy that can be obtained by the methods described, results are given of tests made by ballistic galvanometer as well as by wattmeter methods using identical samples.

The general requirements may be summarized as the following:

1. The accuracy of the test results should be such that the error obtained will be small in comparison with the unavoidable error in making the test sample represent the actual average quality of the material.

2. The dimensions, weight and treatment of the sample should be such that the results may represent the average material from which they are taken as nearly as possible.

3. If without sacrificing unduly other desirable features samples can be used that will be uniform in dimensions, weight, and method of preparation with those used by others, such standard samples should be employed.

4. The entire operation of preparing and testing samples and recording results, should be quickly accomplished and at minimum expense for material and labor.

5. The testing should not require the services of specially trained experts or the use of delicate special instruments.

All the above conditions are not completely met by any apparatus, but we can perhaps make the best progress with the general discussion of the problem from the point of view being presented, by describing two complete sets of apparatus which are being used.

The first uses a one-pound (0.45-kg.) sample made up of strips 10 by ½ in. (25.4 by 1.27 cm.) in dimensions and designed to meet to the fullest possible extent the fourth requirement. The arrangement can be easily used to test the standard sample referred to under requirement three.

The second arrangement was designed specially to meet requirements 1, 2, 3 and 5 using a sample 3 by 50 cm. and weighing 10 kg. (22 lb.) The whole arrangement adheres very closely to the Epstein apparatus already referred to and uses the same size sample.

Discussion of the relative advantages and disadvantages of the two arrangements together with any comparisons with other methods will be deferred until after they have been more completely described and relative test results which have been made on actual samples are given.

Hysteresis Testing Outfit for 10 by ½-in. Samples

The set completely assembled is shown in Fig. 1. The method employed is that of measuring the watts lost in a straight sample using sensitive reflecting dynamometers as wattmeter and voltmeter. For convenience this set is arranged to test samples having a weight of one lb. (0.45 kg.) in a solenoid with open ends returning all the magnetic flux through the air. The height of

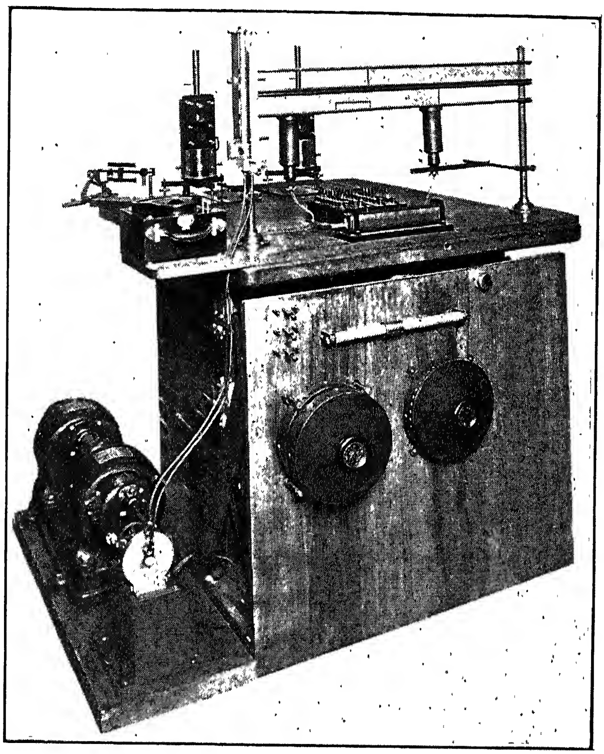


Fig. 1.—Hysteresis testing outfit

sample required is about ¾ in. (19 mm.). On account of the fact that the flux is returned through the air the density B, in the core varies from a maximum at the center to a minimum value at either end of the sample.

The magnetizing current is furnished by a small motor generator set shown in the illustration which is driven from a storage battery. The frequency used is ten cycles at the present time

and the density is equivalent to $B=10,000$ ($6\frac{2}{3}$ cycles was formerly used when tests were made at $B=5,000$). A low frequency was chosen to reduce as much as possible the eddy current loss in the sample so that there would be no serious error in the final result. In practice the eddy losses are usually deducted as a definite fixed sum for a given kind and thickness of material being tested.

There are three windings on the solenoid in which the sample is placed, one to magnetize the sample and one to supply the potential circuit of the wattmeter. The third winding surrounds the middle of the sample and the voltmeter is connected to this, thus determining the flux density at the middle of the sample. The first two windings project over the end of the sample so that a small error in the position of the sample with reference to the windings will produce no error due to a different distribution of flux in the bundle of strips. During a test this voltage is adjusted to give a density at the middle of the sample which will give a hysteresis loss corresponding to the loss with a uniform density throughout the sample of $B=5,000$ or $B=10,000$. The smaller density was first used (from 1897 to 1909) and this was changed to the higher density for tests made since the latter date. The change in density was made so that the test results would conform more nearly to the changed conditions of use and to make the results obtained more readily convertible into terms that could be directly compared with results obtained by other test methods.

The terminals of the magnetizing winding are connected directly to the generator and the exciting current is varied to produce the required deflection on the voltmeter. Current regulation is by means of a rheostat and slider in the field winding of the small generator.

The speed of the generator and therefore the cycles are held constant at the proper value during the test by observing the indications of a liquid tachometer also shown in the illustration. The adjustment of motor speed is made by a rheostat in the motor field. Fig. 2 shows the wiring diagram of the complete arrangement of Fig. 1.

The scales of the wattmeter, voltmeter and tachometer are so arranged that a single observer can conveniently read all of them and record the results without changing his position.

The proper voltage to be used on the sample is determined by weighing it on a special balance shown in Fig. 1 at the left hand back corner at the top of the pier. This balance is graduated

with scales based on a density of 7.8 for standard iron and 7.5 for alloyed iron. These scales connect the voltage with the weight of the sample for both densities. A third scale gives the multiplier to be used for correcting the wattmeter reading to give results for a sample weighing exactly one pound.

The nearest number of strips required to make up one pound is chosen in weighing so that this multiplier is very near unity.

The wattmeter scale is either graduated to read directly in watts per pound at one cycle per second, total loss in the sample, or this quantity is obtained from a table. The graduation or

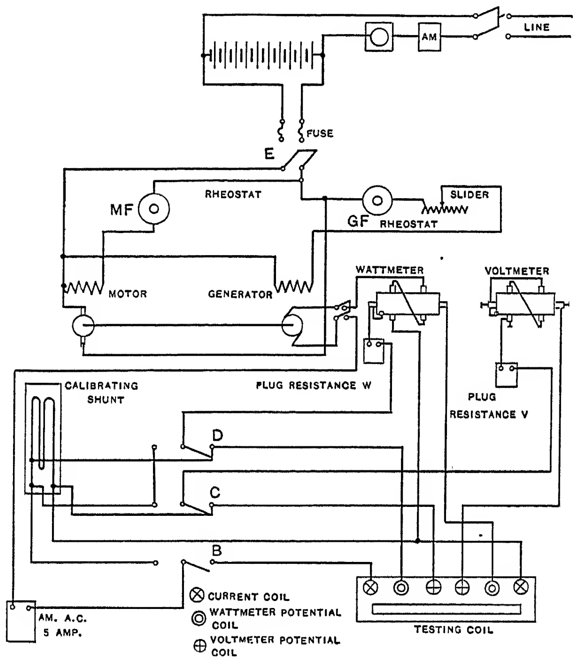


FIG. 2.—Connections of hysteresis testing outfit

the table is so arranged that the loss in the volt coil of the wattmeter and in the voltmeter is deducted. As the eddy loss is different for different kinds of material this is deducted from the final result instead of being corrected for in the graduation of the wattmeter scale or in the table.

The determination of the voltage and number of turns on the volt coil required to produce a magnetization of the sample equivalent in hysteresis loss to that produced by uniform magnetization throughout the sample was determined as follows: Several samples were wound with exploring

coils at various points along their length (usually 21 coils were employed) and the samples carrying these exploring coils were inserted in the testing coil and the flux densities or B values were plotted as ordinates using the distances along the samples as abscissæ.

The ordinate corresponding to each abscissa was then raised to a power corresponding to the hysteresis loss exponent and the curve replotted. The average of this last curve was used to determine the voltage and number of turns corresponding to that which would result from a uniformly magnetized sample. Exponent 1.6 was used in Fig. 3, which gives the general appearance of one of these curves made at a flux density equivalent to uniform magnetization at $B = 8{,}000$. The final determin-

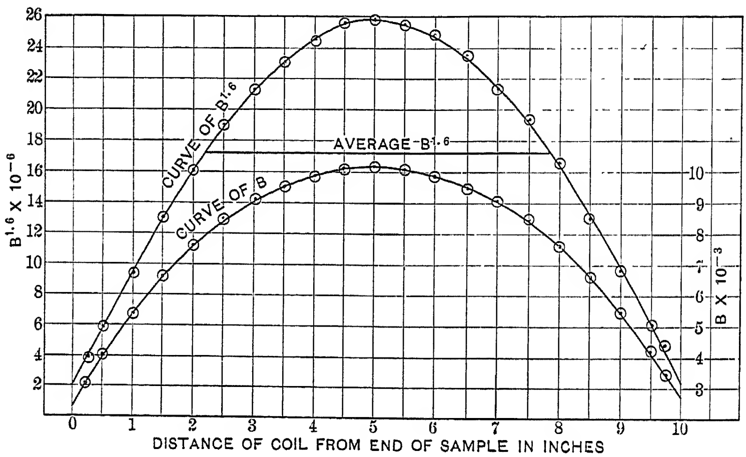


FIG. 3.

ation was arrived at by drawing many curves similar to that shown in the figure but using a higher flux density corresponding to $B = 10{,}000$. The numerous minor details relating to the complete experiments would not be of interest here. It is sufficient to say that a coil located at the center of the sample requires a voltage related to that for a uniformly magnetized sample as 1.3 to 1.

For confirmation of this result see.[1,2]

1. "A method of Determining Magnetic Hysteresis Loss in Straight Iron Strips." By J. A. Fleming, Electrician, (London), June 25, 1897, Vol. 39, No. 9, page 283.

2. "On the Distribution of Magnetic Induction in Straight Iron Rods." By J. L. W. Gill, B.A. Sc. Phil. Mag. S. [5, Vol. 46, No. 282, Nov. 1898, pp. 478, 494.

Consideration of the problem led to the conclusion that if a method of testing using samples in which the distribution of the flux density was so far from uniform could be used at all the proper place for the volt coil was at the center of the sample. The sample need not then be very accurately placed with reference to the volt coil. The results obtained are practically much more exact and theoretically as good as if the volt coil is placed at a point where the turns correspond to the number required for uniform mangetization.

The samples to be tested are inserted into the testing coil and withdrawn from it by means of a wooden holder which can be seen projecting from the testing coil in Fig. 1.

From an enormous number of tests that have been made by this apparatus during the past ten or twelve years the following are selected as representative of the accuracy attainable with the device. The speed of operation is very high, 40 samples have been tested within five minutes at an expense per sample for testing of less than two cents, including punching, annealing, etc., and the recording of the final results. In considering the value of the various arrangements that have been used for testing sheet iron commercially the extreme rapidity and low cost of testing by this method should be given some weight.

Table I shows the results of tests made on several samples with ballistic tests on some of them for comparison.

The reflecting dynamometers used with the small set are calibrated by means of a shunt and ammeter shown in Fig. 2 and the volts and watts on the instruments are computed from the resistance of the calibrating shunt and the current read by the ammeter. This forms a very convenient and accurate means of checking the instruments in place at the frequency of test. The calibrating shunt is divided into two parts having resistances suitable for checking the voltmeter and wattmeter and using only one ammeter for both measurements. It is customary to make such a check once each day or before each set of tests.

Iron Tester for 10-kg. Samples 50 by 3 cm.

This apparatus is shown completely assembled in Fig. 4. The testing coil or sample holder is shown in a later form in Fig. 5. The complete equipment comprises, besides this sample holder, a vibrating-reed frequency indicator shown on the left of table and a portable wattmeter, voltmeter and ammeter of suitable capacity and quality to make the necessary electrical

measurements with the required accuracy. The ammeter is not necessary. The diagram of connections is shown in Fig. 6.

The details of the testing coil shown in Fig. 5 are as follows:

TABLE I
HYSTERESIS TESTING OUTFIT
WATTS LOSS IN SAMPLES 10 BY ½ IN. WEIGHING 1 LB.
0.014″ iron $B = 10{,}000$

Sample No.	Kind of iron	Total loss at 10 cycles	Eddy loss at 10 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by subtraction	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic	Per cent variation hys. by subtraction from ballistic	Epstein equivalent total watts per lb. at 60 cycles
1	Standard	0.205	0.042	0.0163	0.0173	0.0163	0	+6.14	1.586
2	"	0.186	0.036	0.0150	0.0154	—	—	—	1.508
3	"	0.186	0.031	0.0155	0.0154	—	—	—	1.537
4	"	0.184	0.032	0.0152	0.0152	—	—	—	1.520
5	"	0.183	0.032	0.0151	0.0151	—	—	—	1.514
6	"	0.168	0.031	0.0137	0.0136	—	—	—	1.430
7	"	0.171	0.029	0.0142	0.0139	—	—	—	1.460
8	"	0.170	0.029	0.0141	0.0138	—	—	—	1.454
9	"	0.172	0.034	0.0138	0.0140	—	—	—	1.436
10	"	0.202	0.034	0.0169	0.0170	—	—	—	1.622
11	Alloyed	0.131	0.024	0.0107	0.0110	0.0108	—0.93	+1.85	0.822
12	"	0.144	0.016	0.0128	0.0123	0.0123	+4.08	0.00	0.948
13	"	0.141	0.019	0.0122	0.0120	0.0123	—0.82	—2.44	0.912
14	"	0.138	0.023	0.0115	0.0117	0.0116	—0.86	+0.86	0.870
15	"	0.137	0.021	0.0117	0.0116	0.0117	0	—0.85	0.882
16	"	0.133	0.022	0.0111	0.0112	—	—	—	0.846
17	"	0.109	0.018	0.0091	0.0088	—	—	—	0.726
18	"	0.141	0.020	0.0121	0.0120	—	—	—	0.906
19	"	0.128	0.025	0.0103	0.0107	—	—	—	0.799
20	"	0.093	0.024	0.0069	0.0072	—	—	—	0.612
21	"	0.093	0.024	0.0069	0.0072	—	—	—	0.612
22	"	0.095	0.023	0.0072	0.0074	—	—	—	0.624
23	"	0.093	0.023	0.0070	0.0072	—	—	—	0.612
24	"	0.089	0.019	0.0070	0.0068	—	—	—	0.588

The eddy losses used in computing column No. 6 are 0.032 for standard and 0.021 for alloyed iron. These are the average values obtained by separating upwards of 100 samples of each kind of iron. The eddy losses used in computing column No. 10 are 0.608 and 0.180 for standard and alloyed iron respectively.

On a wooden frame so built as to avoid warping four solenoids are mounted into which the four parts of the sample to be tested are inserted, each of these has 150 turns of magnetizing winding and a second winding of 150 turns for supplying the

voltage to the potential coils of the wattmeter and voltmeter. Total number of turns on each winding 600. These windings are laid on at the same time so that they will have exactly the same number of turns located in the same relation to the sample. By this means a voltage corresponding to the flux wave of the sample is impressed on the wattmeter and voltmeter and complicated corrections for the $I\,R$ drop and the $I^2\,R$ loss in the magnetizing winding are eliminated.* This arrangement has been quite generally adopted by those making wattmeter loss measurements in iron samples and is of the greatest advantage in securing convenient and accurate measurements. The advantages of the arrangement are of increasing value as the tests are made at higher magnetic densities where the $I\,R$ and I^2R corrections in any kind of winding become larger

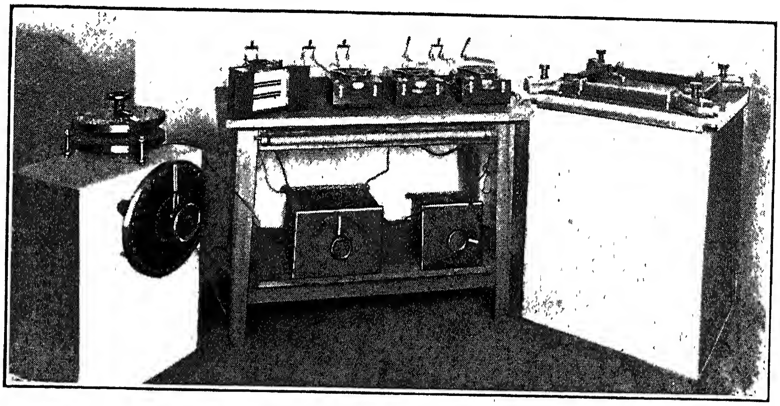


FIG. 4.—Apparatus for testing sheet iron

and where the error due to changed resistance of magnetizing winding due to heating becomes important on account of the large increase of magnetizing current required.

To protect the ends of the coils hard fibre caps are placed over the ends into which the windings are inserted, these end caps are also used to fasten the solenoids to the frame. The four-part sample is assembled into the windings by placing the first portion of the sample against the fibre block shown in the lower part or right hand corner of Fig. 5. This block is cut in such a way that the joint in the sample is completely exposed to view whether the parts of the sample are inserted by passing around the frame in clockwise or counter clockwise direction.

*See C. P. Steinmetz, TRANSACTIONS, A. I. E. E., Vol. 9, 1892, p. 64.

The other three joints require no blocks and all the joints are therefore completely exposed. The samples are clamped in place by the four hinged arms shown extending from the center of the frame and held down by hooks engaging in rollers on the flat phosphor bronze springs below the hinged arms. The form of the hook and the general arrangement is such that the clamping blocks on the edge of the arms are forced down on the ends of the sample with sufficient and definite pressure and still there is no danger of clamping the joints too tightly and therefore increasing the losses in the corners. As compared with the original method of clamping shown in Fig. 4 there is a small but

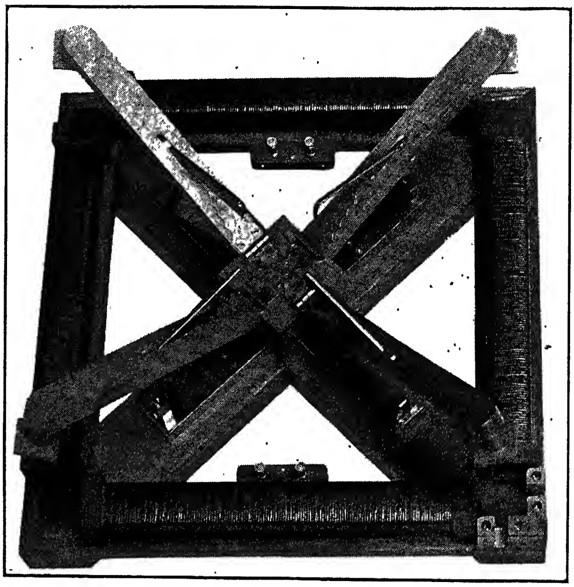


Fig. 5.—Apparatus for testing sheet iron

appreciable advantage that shows itself in the ability of the observer to repeat his measurements on a given sample with less variation among individual observations. This is particularly true when the observations are made by one who is not constantly engaged in testing with the device.

Before the joints at the corners are crowded together a piece of tough paper or fiber about 0.005 in. (0.127 mm.) in thickness is inserted between the joints. The purpose of this paper is to prevent the exposed end of the laminations being forced into the spaces between those in the adjacent side of the other part of the

sample and to prevent the formation of eddy currents at the corners which may not be confined to the thickness of the laminations if the paper is not used. The certainty of the measurements is thereby improved by a small but definite amount over the results which are obtained without the paper in the joints. This improvement is of course accomplished at the expense of some increase of leakage flux at the corners and consequently greater departure from absolute uniformity of flux distribution along the length of the sample, also the conditions imposed upon the wattmeter are more severe as the

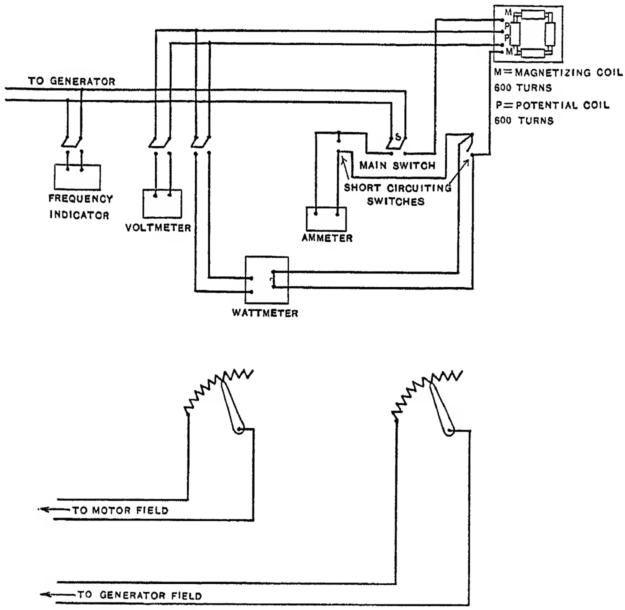


FIG. 6.—Connections of apparatus for testing sheet iron

general power factor is lower. The flux distribution over a section of the sample is more uniform with the paper. The net result is a definite gain in accuracy. The corners are finally forced together by means of a block of wood with a V notch in the end in order to get the joints as firmly together as possible.

The voltage and frequency are adjusted to the proper values and the watts lost in the sample and instrument potential circuits is read. For convenience the total loss per pound (0.45 kg.) at 60 cycles is read directly from a table like Table II. The loss may be expressed as hysteresis loss alone by the usual method of separating, using two or more frequencies or generally with a

sufficient degree of exactness by deducting the proper amount from the total loss at 60 cycles using the average eddy loss determined from a number of previous separations on the same kind of material. The proper amount of material to be used in the four legs of the sample holder is determined by weighing the material in two portions, usually one cut with and the other across the grain, of 11 lb. (5 kg.) each. The weighing is made to the nearest even sheet and each of the 11-lb. bundles is subsequently divided into two equal parts by balancing the parts against one another.

TABLE II
TOTAL IRON LOSS PER LB. AT 60 CYCLES $B=10{,}000$
FOR VARIOUS WATTMETER READINGS
FOR 22 LB. SAMPLE ALLOYED IRON (SP. GR. =7.5)
Resist. of voltmeter =1800 ohms (approx.)
Resist. of wattmeter =1800 ohms (approx.)
Resist. of potential coil of apparatus =7 ohms (approx.)
Voltmeter connected when reading watts

Watts read	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
24	0.529	0.534	0.538	0.543	0.547	0.552	0.557	0.561	0.566	0.570
25	0.575	0.580	0.584	0.589	0.593	0.598	0.603	0.607	0.612	0.616
26	0.621	0.626	0.630	0.635	0.639	0.644	0.649	0.653	0.658	0.662
27	0.667	0.671	0.676	0.681	0.685	0.690	0.694	0.699	0.703	0.708
28	0.713	0.717	0.722	0.726	0.731	0.736	0.740	0.745	0.749	0.754
29	0.758	0.763	0.768	0.771	0.776	0.781	0.786	0.791	0.795	0.800
30	0.804	0.809	0.813	0.818	0.823	0.827	0.832	0.836	0.841	0.845
31	0.850	0.855	0.859	0.864	0.868	0.873	0.878	0.882	0.887	0.891
32	0.896	0.900	0.905	0.910	0.914	0.919	0.923	0.928	0.932	0.937
33	0.942	0.946	0.951	0.955	0.960	0.965	0.969	0.974	0.978	0.983
34	0.987	0.992	0.997	1.001	1.006	1.010	1.015	1.020	1.024	1.029
35	1.033	1.038	1.042	1.047	1.052	1.056	1.061	1.065	1.070	1.074
36	1.079	1.084	1.088	1.093	1.097	1.102	1.107	1.111	1.116	1.120
37	1.125	1.129	1.134	1.139	1.143	1.148	1.152	1.157	1.161	1.166
38	1.171	1.175	1.180	1.184	1.189	1.194	1.198	1.253	1.207	1.212
39	1.211	1.216	1.221	1.225	1.230	1.234	1.239	1.244	1.248	1.253
40	1.262	1.267	1.271	1.276	1.281	1.285	1.290	1.294	1.299	1.303

The following table No. III gives comparison of ballistic determinations with those on the 50 by 3-cm. samples. The ballistic measurements which were made on the various samples for comparison were made by a method substantially like that first described by Vignoles*, and will not be referred to in detail here. Three windings were placed on the samples one for con-

**Electrician*, (London) May 15, 1891, Vol. XXIII, page 49.

TABLE III
APPARATUS FOR TESTING SHEET IRON
WATTS LOSS PER LB. IN 22 LB. 0.014″ EPSTEIN SAMPLES. $B = 10{,}000$

Sample No.	Kind of iron	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by subtraction	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic	Per cent variation hys. by subtraction from ballistic
1	Standard	1.725	0.615	0.0185	0.0186	0.0188	—1.59	—1.06
2	"	1.811	0.641	0.0195	0.02005	0.0188	+3.72	+6.40
3	"	1.565	0.617	0.0158	0.0159	—	—	—
4	"	1.735	0.439	0.0216	0 0186	—	—	—
5	"	1.7081	0.586	0.0187	0.0183	—	—	—
6	"	1.465	0.601	0.0144	0.0143	—	—	—
7	Alloyed	0.894	0.186	0.0118	0.0119	0.0118	0.00	+0.85
8	"	0.894	0.156	0.0123	0.0119	0.0122	+0.82	—2.46
*7	"	0.891	0.177	0.0119	0.0118	0.0118	+0.85	0
*8	"	0.891	0.153	0.0122	0.0118	0.0122	0	+3.28
9	"	0.896	0.176	0.0120	0.0119	0.0117	+2.56	+1.71
10	"	0.929	0.197	0.0122	0.0125	0.0124	—1.64	+0.81
11	"	0.920	0.182	0.0123	0.0122	0.0121	+1.66	+0.83
12	"	0.748	0.166	0.0097	0.0095	—	—	—
13	"	0.793	0.199	0.0099	0.0102	—	—	—
14	"	0.883	0.133	0.0125	0.0117	—	—	—
15	"	0.806	0.176	0.0105	0.0104	—	—	—
16	"	0.774	0 180	0.0099	0.0099	—	—	—
17	"	0.738	0.150	0.0098	0.0093	—	—	—
18	"	0.767	0.179	0.0098	0.0098	—	—	—
19	"	0.767	0.167	0.0100	0.0098	—	—	—
20	"	0.747	0.165	0.0097	0.0094	—	—	—
21	"	0.882	0.156	0.0121	0.0117	—	—	—
22	"	0.688	0.124	0.0094	0 0085	—	—	—
23	"	0.930	0.186	0.0124	0.0125	—	—	—
24	"	0.894	0.174	0.0120	0.0119	—	—	—
25	"	0.605	0.212	0.00655	0.0071	—	—	—
26	"	0.669	0.142	0.0088	0.0082	—	—	—
27	"	0.671	0.135	0.0089	0.0082	—	—	—
28	"	0.671	0.167	0.0084	0.0082	—	—	—

The eddy used in computing column No. 6 are 0.608 and 0.180 for standard and alloyed iron respectively.

*Results obtained by using reflecting instruments on two of above samples.

nection to the ballistic galvanometer and the other two for carrying the samples through the magnetic cycle.

Experience has shown that the method of testing using a step-by-step method as originally used by Ewing sometimes gives results that are not the same as those obtained on identical samples when tested by the wattmeter method. On the other hand ballistic measurements by the method employed usually show very close agreement with wattmeter tests. The ballistic tests made on the straight strips of both the one-lb. and 22-lb. samples were taken on the samples assembled with

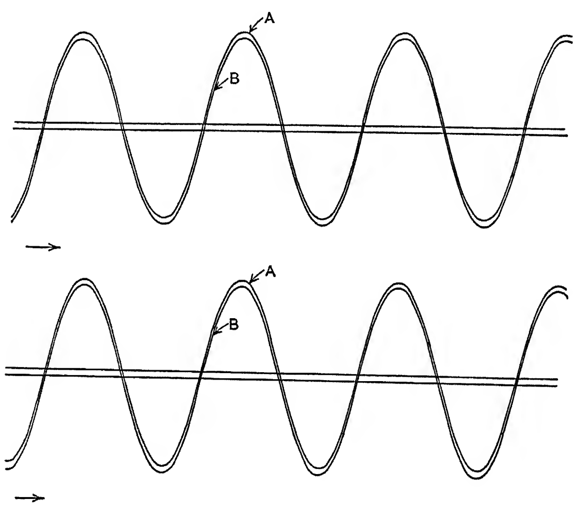


FIG. 7.—Apparatus for testing sheet iron.
22 lb. sample in test
Generator TH Form A18
A, wave of e.m.f. on magnetizing winding
B, wave of induced e.m.f. in volt winding
Upper record, *B* in sample = 10,000
Lower record, *B* in sample = 15,000

lapped joints and not with butt joints or in the open end testing coil which was used in the actual wattmeter testing.

Any generator that gives a sine wave under the small load used is suitable for testing the 22-lb. samples. The generator for the small set using the one-lb. samples is special because of the low frequency and low voltage employed.

The wave of e.m.f. used on the magnetizing windings of the large set and the wave of induced e.m.f. in the volt winding are shown in Fig. 7. It will be seen from inspection of the waves that the original wave of e.m.f. impressed on the magnetizing winding is satisfactory and that the apparatus is so constructed

that there is no appreciable distortion in the flux wave in the sample under test. Form factor has been computed for the waves and shows them to be sinusoidal within the limits of error of the measures.

The inequality of distribution of flux along the large samples does not amount to more than 8 per cent.* The resulting error from this cause does not exceed a fraction of one per cent.

It may be of advantage to give results of some tests on rings made by the ballistic method and also by using wattmeters. These results show that under conditions that may be considered free from any errors due to assembling cut samples in various forms there is a good agreement between the results obtained by wattmeter separation and by ballistic measurements. Although this may not show anything very definite it shows that the results obtained in testing the cut samples are either correct or else that the ballistic determinations are affected to the same degree and in the same direction as the wattmeter measurements Table VI gives results in detail.

TABLE IV

APPARATUS FOR TESTING SHEET IRON

WATTS LOSS PER LB. IN 22 LB. EPSTEIN SAMPLES. 0.014 ALLOYED IRON

$B = 15{,}000$

Sample No.	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec.
1	1.938	0.204	0.0289
2	1.969	0.265	0.0284

The requirements imposed on the wattmeter in testing on both sets are somewhat severe because of the low power factor. This is about 30 per cent at $B = 10{,}000$ to 10 per cent at $B = 15{,}000$ on the large set and 10 per cent on the small set. The reflecting dynamometers are constructed in such a way as to be free from any error due to low power factor, this point has been checked by testing them on an ironless reactance of carefully stranded conductor and the portable instruments of commercial type have been tested by comparison with the reflecting instruments and show no sensible error under the conditions of use.

These portable instruments are constructed to give full scale deflection with about 25 per cent power factor, and hence give a much larger deflection when used on this work than could be obtained on instruments built to meet the ordinary requirements of testing at high power factor.

*From results communicated by A. B. Hendricks.

Before passing to a discussion of the results obtained with reference to the requirements first outlined table V will be referred to which is convenient for transforming results which are given in different terms to the same basis. By means of this table the results expressed in any of the usual terms may be readily converted into any other form. Such a table must of course include average eddy determinations as it has been the practice to sometimes state the result in hysteresis loss alone or to sometimes give total loss. Considering the fact that eddy loss is largely a function of the apparatus in which the iron is used and not

TABLE V

CONVERSION TABLE

FOR ALLOYED IRON SPECIFIC GRAVITY = 7.5. MULTIPLYING FACTORS FOR COMPARING RESULTS OF IRON TESTS QUOTED ON VARIOUS BASES

TO / FROM	Hys. watts per lb. per cycle at 1 cycle per sec. $B=5{,}000$	Hys. watts per lb. per cycle at 1 cycle per sec. $B=10{,}000$	Epstein total watts per kilo. 50 cycles $B=10{,}000$	Epstein total watts per lb. 60 cycles $B=10{,}000$	Hys. ergs. per cm. per cycle $B=10{,}000$	Hys. ergs. per gram per cycle $B=10{,}000$
Hys. watts per lb. per cycle at 1 cycle per sec. $B=5{,}000$		× 3.03	×333.3 + 0.275	×181.8 + 0.18	×500,980	×66,797
Hys. watts per lb. per cycle at 1 cycle per sec. $B=10{,}000$	×0.33		×110 +0.275	×60 +0.18	×165,340	×22,045
Epstein total watts per kilo. 50 cycles $B=10{,}000$	— 0.275 ×0.0030	— 0.275 × 0.00909		× 0.545 + 0.03	—0 275 ×1,504	— 0 275 ×200.5
Epstein total watts per lb. 60 cycles $B=10{,}000$	— 0.180 × 0.0055	— 0.180 × 0.0167	— 0.03 × 1.835		—0.180 ×2,756	— 0.180 ×367.5
Hys. ergs. per cm. per cycle $B=10{,}000$	× 1.996 $\times 10^{-6}$	× 6.045 $\times 10^{-6}$	×665 $\times 10^{-6}$ + 0.275	×363 $\times 10^{-6}$ + 0.180		×0.1333
Hys. ergs. per gram per cycle $B=10{,}000$	×14.97 $\times 10^{-6}$	×45.35 $\times 10^{-6}$	×4,988 $\times 10^{-6}$ + 0.275	×2,723 $\times 10^{-6}$ + 0.180	×7.5	

wholly a function of the material; it is, unless separation tests are made on all samples, as accurate to convert test results from one form to another by this table as it is to give the results of total loss determination alone. The only reason that total loss determinations are of value in connection with any sort of testing apparatus is that the eddy loss is near enough constant so that the total loss is approximately a measure of the magnetic quality of the material. It must be borne in mind that close agreement between total loss measurements on any given apparatus does not mean that the accuracy is sufficiently good for practical

purposes unless the separated eddy for a given material is near enough to a constant value to make the hysteresis loss determined by subtraction very nearly that which would be obtained if actual separation was always made. These statements are made on the assumption it would not be permissible to consider any test as a test commercially possible which required several readings and a consequent separation by usual methods.

Some idea of the relation between the tests on individual samples and the general quality of the material under test can be obtained when it is stated that samples 1, 2, 3, 4 and 5 of table VI are from the same lot of material. The mean value of all of these samples is 1.27 and the difference between the highest and lowest is 0.008 or a variation of 3 per cent from the mean. Referring to table III there are also five samples from one lot of material, *viz.*, 7, 8, 9, 10, 11. The mean value of the measure-

TABLE VI

WATTS LOSS PER LB. IN 20 LB. RING SAMPLES 0.014″ ALLOYED IRON $B = 10,000$

Sample No.	Total loss at 60 cycles	Eddy at 60 cycles	Hys. per cycle at 1 cycle per sec. by separation	Hys. per cycle at 1 cycle per sec. by ballistic	Per cent variation hys. by separation from ballistic
1	0.932	0.158	0.0129	0.0125	+3 20
2	0.943	0.193	0.0125	0.0126	—0.80
3	0.963	0.177	0.0131	0 0131	0.00
4	0 953	0.191	0.0127	0.0126	+0.80
5	0.922	0.184	0.0123	0.0121	+1.65

ments on these is 1.21 the variations between the highest and lowest 0.005 or about 2 per cent from the mean. Reference to table No. 1 shows five samples Nos. 11, 12, 13, 14 and 15, from one lot of material tested on a small set having a mean value of 1.18 a variation between extremes of 0.021 or 9 per cent from the mean. This variation is almost entirely caused by sample No. 11 but this could not be excluded and shows one disadvantage of the small sample, unless care is taken to distribute the punching throughout the material to be tested. It is believed that in this way just as accurate results can be obtained as with larger samples and they may be easily chosen from different parts of the lot of steel so as to obtain an accurate measure of this quality without completely destroying the sheets for the purpose for which they are to be used. The samples referred to in the tables were not chosen

with any definite purpose of determining the quality of the material from which they were taken but were simply selected to get comparative tests by different methods.

All the samples were annealed after cutting and before testing. Of course the disadvantage of the small samples becomes very great if the testing of the samples must be done before annealing. As a workshop method there can be no advantage in testing without annealing, but for a standard method a sample should be chosen of dimensions such that the cutting does not change the quality by an appreciable amount. More recently it has become the part of certain requirements to give test results for $B=15{,}000$. Table IV shows results at this density on two samples with the total and separated loss measures. The advantages of the separate volt winding becomes quite apparent at this density also reference to Fig. 3 will show that the small set is not applicable to testing at this density. The details of the separation tests that were made on the various samples will not be given further than to state that on the small set 10, 13, 16 and 19 cycles were used and on the 22-lb. samples 25, 30, 40, 50 and 60 cycles were used. It is believed that separation at two extreme cycles is satisfactory but in this particular work it was felt that some degree of precision was added by making observations at two or three intermediate frequencies.

In giving results of tests made by the two arrangements which have been described it is not possible to include more than a small part of the total number of samples that have been tested. It may be well to call attention to this point before passing to the conclusions as it will no doubt be impossible to exclude from consideration results that are not referred to in the tables. The tables therefore should be accepted as a general indication of the results obtained rather than representing sufficient data from which conclusive averages may be derived. In no case have conclusions affecting the procedure to be followed in the work been reached on a basis of less than 100 samples tested and usually many times this number have been considered.

The accuracy that can be obtained in testing the one-lb. samples should be considered as subject to a possible variation of 5 per cent from the actual hysteresis loss in any given sample. As the eddy loss in testing this form of sample has no direct connection with the eddy loss that would occur in completed apparatus, statement of total loss determinations in the open end testing coil cannot be considered. The apparatus which tests the Epstein samples will give total loss within about 2 per

cent of the true value and hysteresis loss without separation usually within somewhat closer limits than figures given for the small set. Due to the fact that the eddy loss found in testing the Epstein samples represents very nearly that which is found in ordinary transformers, total loss determinations on the 22-lb. samples have some value without deducting the eddy. On the whole the accuracy with this arrangement must be considered superior to that obtained in the open end testing coil.

The accuracy obtainable with either arrangement is believed to be well within the limits of the ability of the producers of sheets to secure uniformity of product and of designers to produce definite results with material of uniform and known quality. We are speaking now of the errors in testing individual samples and of course in speaking of material and apparatus we must use the same terms and consider that single sheets of material and individual transformers, for instance, are referred to. We may then consider that the accuracy with either method is satisfactory and take up the other requirements which were referred to in the beginning of the paper.

The accuracy of sampling with the 22-lb. sample is within 3 or 4 per cent for fairly uniform material. The accuracy of sampling with the one-lb. samples may give errors as much as 10 per cent but this can be reduced by careful attention in choosing the samples. It is more difficult to reach a definite conclusion on this point than on any other and to support any opinion by properly arrayed facts. It would seem fair to state that five of the small samples may be so chosen as to give a result as good as could be obtained with one of the 22-lb. samples and destroy less material for the test.

With reference to the third requirement it should be possible to directly compare results obtained by different methods without the necessity of recourse to ballistic galvanometer tests. On account of the extensive use that has already been made of Epstein apparatus it would seem that not much argument is required to show that the 50- by 3-cm. sample should be chosen as the standard size and that any standard method of measurement should be based on testing a sample of this dimension either 22-lb. at once or in several parts. In this way all considerations of the preparation of the material can be made general and will affect all the tests alike. While the method of measurement which uses the open end testing coil has not been employed commercially to test the samples of larger dimensions, it has been shown experimentally that it would be equally satis-

factory in operation using a definite portion of the complete 22-lb. sample.

With reference to the fourth requirement it is difficult to give estimates of the cost of testing by the various methods which have been proposed. It is believed that including the cost of material the expense per sample tested would be at least 10 to 20 times with the modified Epstein arrangement what it would be with the small set. On the other hand the successful employment of the small set so far requires the use of a steady pier and instruments which are not to be considered as ordinarily suited to workshop requirements. As a final conclusion it is felt that the small set is eminently suited to such situations as require a very large number of tests where the cost of the labor and material in testing is important. Such situations would usually permit of the employment of at least one man with the necessary degree of intelligence and experience to keep the accuracy of the results within required limits.

For situations where the total number of tests to be made is not sufficient to maintain a permanent organization for the work the Epstein arrangement is most satisfactory and it is believed that the form described is in some respects superior to the original arrangement. The amount of material required is somewhat large but the results obtainable are accurate enough to leave nothing desired from this point of view. The whole equipment is strong and can be operated by any one of ordinary intelligence and without special training. Because this method possesses the above desirable features to a marked degree it should become ultimately the universally accepted standard method of testing.

It would not be proper to leave the subject without referring briefly to the method of testing which has already been cited in the reference on the first page of this paper and which was developed by the National Bureau of Standards. The accuracy obtainable by this method is undoubtedly superior to that of any previously described and the method therefore marks a distinct advance in the art. The increase in accuracy over previous methods similar to those described is not sufficient to be of importance in practical work. The use of this apparatus it is believed will be found chiefly in connection with accurate research work on relatively small samples of material. The added accuracy is obtained at the expense of increased length of time required to assemble and test the samples.

A paper presented at the 261st meeting of the American Institute of Electrical Engineers, New York, April 14, 1911.

THE EFFECT OF TEMPERATURE UPON THE HYSTERESIS LOSS IN SHEET STEEL

BY MALCOLM MAC LAREN

In the experiments described below, investigations were made upon the variation in hysteresis loss in sheet steel when passing from ordinary atmospheric temperatures up to the point at which the material becomes non-magnetic. The measurements were made over as wide a range of induction as possible. In order to get consistent results it was found to be important that the observations at each temperature be made quickly, partly on account of the difficulty of holding the temperature constant and partly because, even with constant temperature slow changes occurred in the hysteresis which become especially pronounced at the higher temperatures.

Method of Measurement. The method of measurement which was employed was a modified form of the well known two-frequency method in which alternating current is applied to the test sample and the combined hysteresis and eddy current loss is measured. The hysteresis loss $= a f B^x$ and the eddy current loss $= \beta f^2 B^2$, where a and β are constants, f is the frequency in cycles per second, B is the induction per square centimeter, and x is an unknown quantity equal to approximately 1.6.

If w_1 = the measured loss at a frequency f_1 and w_2 = the measured loss at a frequency f_2 then

$$w_1 = a f_1 B^x + \beta f_1^2 B^2$$

and

$$w_2 = a f_2 B^x + \beta f_2^2 B^2$$

Solving these equations for β at any induction B we get:

$$\beta = \frac{w_1 f_2 - w_2 f_1}{B^2 \left(f_2 f_1^2 - f_1 f_2^2\right)}$$

Knowing β, the eddy current loss can be determined and by subtracting this from the measured loss the hysteresis can be obtained. In making the measurements it is desirable to use a low frequency for the lower limit as then the measured loss is principally hysteresis. The higher frequency should be considerably above the lower in order that errors in observations should not introduce too great an error in the determination of β. In all these experiments 25 and 60 cycles were the two frequencies used.

If measurements had been made upon the sample through a single exciting coil a correction would have been necessary on account of the $I^2 R$ loss in this coil. This is difficult to make accurately with varying temperature and has been avoided in this case by placing a primary and secondary winding upon each sample.* If the current coil of the wattmeter is connected into the primary and the potential coil across the secondary, then the combined hysteresis and eddy current loss will equal the wattmeter reading multiplied by the ratio of the primary to the secondary turns. The corresponding induction is found from the formula:

$$B = \frac{V \times 10^8}{\sqrt{2} \times \pi \times A \times f \times S}$$

where V = secondary voltage.

A = cross section of sample in square centimeters.

S = number of secondary turns.

The arrangements of connections is shown in Fig. 1. The ammeter in the primary circuit was not required in determining the hysteresis loss but was useful in following the change in magnetizing current as the material approached saturation. Instruments were used which contained no iron in their magnetic circuits and were, therefore, not affected by a change of frequency. The wattmeter was calibrated for low power-factor and was compensated for the loss in its potential coil. It was necessary, however, to correct for the loss due to the voltmeter

* Due to Dr. Steinmetz, TRANSACTIONS of A. I. E. E., Vol. IX.

current. This was done by observing the difference in the wattmeter readings with the voltmeter circuit closed and open at constant voltage. A number of such readings were taken from which a curve was plotted showing the voltmeter loss for any voltage over the range covered by the experiments.

The alternator used during the test gave an e.m.f. wave of approximately sine form and was of sufficient capacity to have its field practically unaffected by the maximum armature current of 2.5 amperes required for the test sample. Distortion of the wave form was further minimized by connecting the primary winding directly across the terminals of the alternator and varying the voltage applied to the sample by varying the field excitation. The alternator was direct coupled to an interpole shunt-wound motor in which the speed could be varied from 750 to

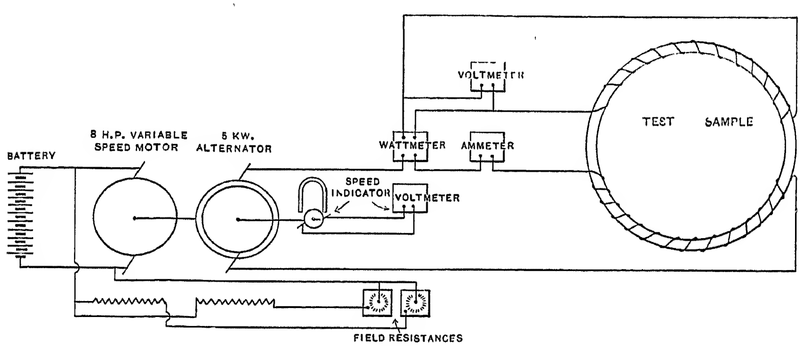


FIG. 1

1800 rev. per min. by varying the field excitation. These limits corresponded to 25 and 60 cycles at the alternator. A magneto speed indicator, direct coupled to the motor generator set, allowed the frequency to be determined instantly, and permitted the change from one test frequency to the other to be made very quickly. A storage battery was used for supplying power to the motor, so that the voltage and frequency at the sample remained very steady while the observations were being made.

This method of measurement was checked by comparing results with direct measurements of the hysteresis loop for several inductions in the manner described below.

The temperature was determined by platinum-iridium thermocouples and a potentiometer. As a check two couples were used in each experiment and were placed in opposite sides of the

sample. Differences of temperature of one degree could be noted with these couples.

Electric Furnace. The furnace used for heating the sample is shown in section in Fig. 2. The inside heater *A* consisted of a corrugated porcelain dish with "nicrome" heating wire wound in the corrugations. The outside heater *B* was made up of a sheet steel cylinder insulated with a thin layer of asbestos, about this were wound fifteen turns of "nicrome" wire; strips of asbestos were placed between turns and the whole was covered with a thick layer of asbestos. Alternating current was used for the heater and the temperature was controlled through regulating transformers. The sample *S* was heated uniformly by

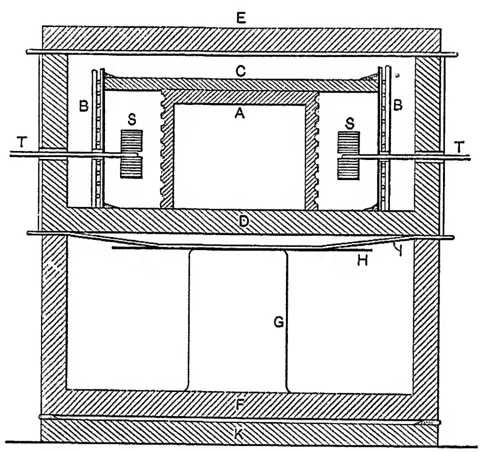


Fig. 2

placing it in the center of the heating chamber. This chamber was closed at the top by a fire clay disk *C* which rested upon the top of the inside heater and fitted closely against the inside surface of the outside heater. An intermediate chamber was formed by placing the heaters in a fire clay pot *D* and closing the top with a disk of thick asbestos and a fire clay cover *E*. The outside of the furnace was covered with asbestos. All joints were sealed with clay. Small holes were cut in the sides of the retaining vessel and in the outside heater to allow the entrance of the thermo-couples *T* and these holes were sealed with asbestos.

The flow of heat through the bottom of the furnace was checked by mounting this upon a second fire clay pot *F* in which thermal currents were broken up by means of a glass dish *G*, a

glass plate H and an asbestos disk I. The furnace was further insulated from the floor by a fire clay disk K.

The maximum power taken by the furnace during the experiments was 1500 watts. This gave an average temperature rise of about 100 deg. cent. per hour.

Test Samples. Measurements were made upon three samples. The same material was used in samples No. 1 and No. 2 and corresponded to a good grade of commercial armature steel. The average thickness of the plates was 0.43 mm. The essential difference between these samples was that in No. 2 the eddy currents which might exist between plates was checked by placing very thin strips of mica between every second plate. Sample No. 3 was made up of high silicon transformer steel the average thickness of plate being 0.349 mm. In each case the rings were 2.54 cm. wide and had a mean diameter of 27.9 cm. They were separated at the center by U-shaped spacing strips to allow the introduction of the thermo-couples. The primary winding consisted of a single layer of iron wire distributed uniformly around the sample and insulated from the steel rings by sheet asbestos reinforced with mica near the terminals. This was covered with a thin layer of Portland cement and a second layer of asbestos. The secondary was wound upon this and the sample was then covered with a second layer of Portland cement. Further details which differed in the three cases were as follows:

	Cross section	Primary turns	Sec. turns	Weight
Sample No 1..............	14.0 sq. cm.	195	166	9.6 kg.
" No. 2..............	12.9 "	144	156	8.874 "
" No. 3..............	13.27 "	154	161	8.611 "

Results. In each case observations were taken at several temperatures first at 25 cycles, then at 60 cycles and then a few check readings were again made at 25 cycles to see that the losses had not changed while the measurements were being made. The results were then plotted in the form of curves between loss per kilogram and induction, the observed points being indicated in each case. From these curves β, the coefficient of the eddy current loss, was first determined and from this the eddy current loss was separated from the hysteresis for 25 cycles at several different inductions. Finally curves were derived which

showed the change in hysteresis loss with the temperature at constant induction.

Sample No. 1. After the test had been started on this sample and the temperature had reached about 150 deg., measurements indicated that a short circuit was developing in the windings. The test had to be discontinued, but the temperature was raised to about 400 deg. in the hope of removing the defect. Later measurements after the cooling showed that the short circuit had disappeared and the test was continued up to the non-magnetic point. It was found, however, that above 500 deg. the losses increased with rise of temperature which was probably due to a reappearance of the short circuit, so that the measurements above this point are not of great value except as they serve to check the results obtained on sample No. 2. Table I shows the value of β and the corresponding values of eddy current and hysteresis loss at 25 cycles for this series of observations. The average value of β for each temperature has been used in the determination of the eddy current loss except for the highest temperatures where this does not seem permissible.

It might seem that variations of 15 or 20 per cent in the values of β which occur in the test would indicate correspondingly large errors in the observations and give very inaccurate results in the determination of the hysteresis loss. It should be remembered, however, that $\beta = \dfrac{w_1 f_2 - w_2 f_1}{B^2 (f_2 f_1^2 - f_1 f_2^2)}$ in which the measured losses affect the numerator only.

Taking one of the worst cases, which occurs in the measurements at 282 deg. for B equal 10,000, when the value of β is about 20 per cent less than the average, the measurements showed that $w_1 = 2.94$ and $w_2 = 1.05$ and the numerator in the above was therefore $2.94 \times 25 - 1.05 \times 60 = 10.5$. In order that the observed value of β should equal the average this figure should be increased to 13 and this difference would be accounted for by an error of about 3 per cent in the value of w_1 or about 4 per cent in the value of w_2 . . It will also be seen from the table that at this point the eddy current loss equals 0.155 watt per kg. out of a total measured loss of 1.05 watts per kg. This means that even with an error of 20 per cent in the determination of the eddy current loss the error introduced in the value of the hysteresis loss would only amount to 4 per cent.

Fig. 3 was plotted from the values for the hysteresis loss given in the table. The break in the curves between 150 and 200 is accounted for the fact that the test was not continuous.

TABLE I

B	24 deg. cent.			140 deg. cent.			197 deg. cent.		
	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
14000	0.0456	0.61	2.24	0.0284	0.41	2.20	0.0291	0.384	1.90
12000	0.0462	0.45	1.57	0.0345	0.301	1.53	0.0305	0.284	1.37
10000	0.0510	0.312	1.06	0.0330	0.218	1.05	0.0306	0.196	0.944
8000	0.0515	0.200	0.72	0.0350	0.134	0.716	0.0315	0.126	0.615
6000	0.0550	0.112	0.448	0.0365	0.075	0.445	0.0355	0.071	0.367
Average..	0.0499			0.0335			0.0315		

282 deg. cent.			390 deg. cent.			460 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0290	0.304	1.71	0.0256	0.325	1.32	0.0319	0.385	1.05
0.0218	0.223	1.28	0.0245	0.240	1.01	0.0294	0.285	0.825
0.0200	0.155	0.895	0.0243	0.166	0.718	0 0267	0.197	0.603
0.0244	0.099	0.581	0.0256	0.107	0.466	0 300	0.126	0.394
0.0291	0.056	0.344	0.0333	0.060	0.268	0.0350	0.071	0.219
Av. 0.0248			0.0266			0.0316		

535 deg. cent.			600 deg. cent.			665 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0410	0.481	0.829	0.0613	0.690	0.655			
0.0390	0.354	0.668	0.0595	0.510	0.525			
0.0360	0.246	0.492	0.0552	0.352	0.398	0.147	0.92	0.19
0.0370	0.157	0.323	0.0501	0.225	0.265	0.132	0.53	0.17
0.0435	0.089	0.161	0.0549	0.127	0.134	0.121	0.27	0.098
Av. 0.0393			0.0562					

708 deg. cent.			749 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
—	—	—	—	—	—
—	—	—	—	—	—
0.147	0.92	0.105	—	—	—
0.133	0.53	0.130	0.216	0.86	—0.15
0.121	0.27	0.083	0.179	0.40	—0.04

Sample No. 2. Fewer primary turns were used in this case than with sample No. 1 in order to get greater clearance between turns and more care was taken with the insulation, as a result there was no indication of any failure of insulation during

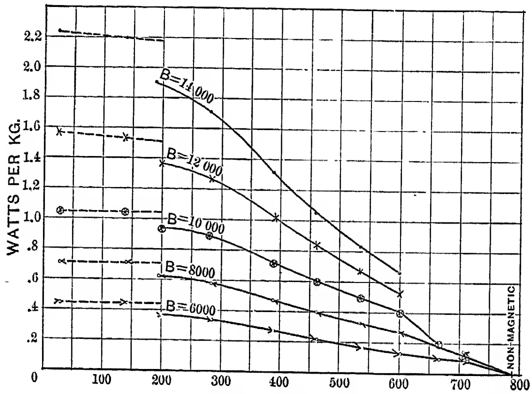


FIG. 3

the test upon this sample. The measured losses in this case, which are representative of the three sets of measurements, are shown in Figs. 4 and 5, the value of β and the corresponding eddy current and hysteresis losses are given in Table II and the

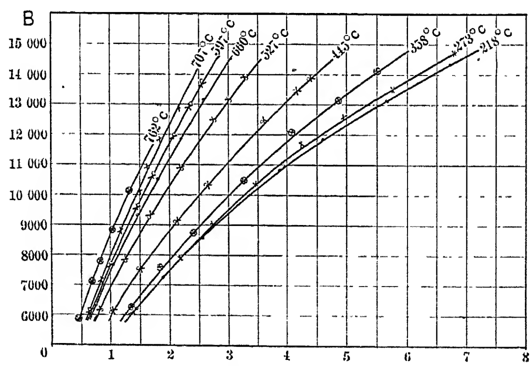


FIG. 4

values of the hysteresis loss shown in the table are plotted with reference to temperature in Fig. 6.

Comparing Figs. 3 and 6 it will be seen that the two samples show the same general characteristics. They both show a remarkably small change in loss at the lower temperatures; they

also both show a sudden drop in the curves although this occurs at about 100 deg. higher temperature on sample No. 2 than on sample No. 1. Perhaps too much reliance should not be placed upon the results obtained with sample No. 1 on account of its

TABLE II

B	218 deg. cent.			273 deg. cent.			358 deg. cent.		
	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
14000	0.0342	0.421	1.66	0.0342	0.407	1.55	0.0259	0.320	1.49
12000	0.0341	0.310	1.23	0.0328	0.299	1.19	0.0242	0.235	1.16
10000	0.0348	0.216	0.884	0.0318	0.207	0.869	0.0256	0.164	0.866
8000	0.0345	0.138	0.582	0.0340	0.133	0.597	0.0274	0.105	0.595
6000	0.0351	0.077	0.375	0.0337	0.075	0.377	0.0275	0.059	0.371
Average	0.0345			0.0332			0.0261		

445 deg. cent.			527 deg. cent.			597 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0240	0.277	1.16	0.0208	0.265	0.765	0.0190	0.251	0.519
0.0226	0.203	0.937	0.0203	0.195	0.625	0.0192	0.185	0.435
0.0220	0.141	0.699	0.0223	0.135	0.465	0.0191	0.128	0.347
0.0218	0.091	0.479	0.0222	0.087	0.318	0.0192	0.084	0.246
0.0225	0.051	0.299	0.0230	0.049	0.191	0.0245	0.046	0.135
Av. 0.0226			0.0217			0.0205		

660 deg. cent.			707 deg. cent.			762 deg. cent.		
$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.	$\beta\times10^{10}$	Ed.	Hyst.
0.0270	0.361	0.354	0.0250	0.335	0.253	—	—	—
0.0282	0.265	0.285	0.0248	0.246	0.234	—	—	—
0.0292	0.184	0.244	0.0256	0.171	0.197	0.0357	0.223	0.002
0.0308	0.118	0.172	0.0269	0.109	0.149	0.0360	0.144	0.009
0.0323	0.066	0.099	0.0346	0.061	0.084	0.0364	0.082	-0.001
Av. 0.0295			0.0273					

defective insulation but it is suggestive to note that from 200 to 400 deg. the rate of heating in No. 1 was 80 deg. per hour and in No. 2 it was 35 deg. per hour and this might be a possible explanation of the differences which occur in the two samples over this range of temperature.

It is possible that sufficient refinement was not entered into in these measurements to enable an accurate determination to be made of the exponent x in the expression, hysteresis loss $w=a\,f\,B^x$; but the results are so consistent among themselves and check so well with the direct measurement of the

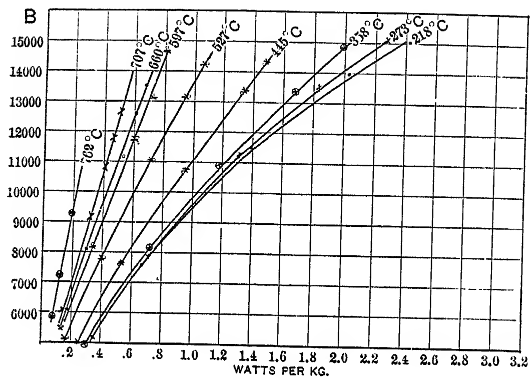


FIG. 5

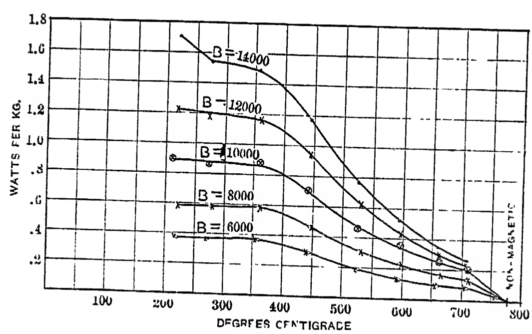


FIG. 6

hysteresis loops, that comparative values at different temperatures should be fairly correct. Transforming the above expression into the logarithmic form,

$$x = \frac{\log w - \log (a\,f)}{\log B}$$

a preliminary investigation showed that x was practically constant so that at each temperature this was assumed equal to

1.6 at the minimum induction and a value was obtained for the constant log $(a f)$ which changes only with the temperature. The value of x at the higher inductions was then obtained by using the values of w given in table II. The results are shown below and indicate that the law governing the change of hysteresis loss with the induction is unaffected by the temperature even near the non-magnetic point.

B	218 deg. cent.	237 deg. cent.	358 deg. cent.	445 deg. cent.	527 deg. cent.	597 deg. cent.	660 deg. cent.	707 deg. cent.
6000	1.600	1.600	1.600	1.600	1.600	1.600	1.600	1.600
8000	1.598	1.600	1.601	1.601	1.605	1.615	1.610	1.160
10000	1.604	1.602	1.602	1.603	1.608	1.606	1.609	1.604
12000	1.608	1.604	1.603	1.603	1.608	1.606	1.594	1.591
14000	1.614	1.606	1.604	1.600	1.603	1.600	1.591	1.570

Sample No. 3. The results of the test upon this sample are shown in table III, and the variation of the hysteresis loss with the temperature is shown in Fig. 7.

TABLE III

B	47 deg. cent.			300 deg. cent.			402 deg. cent.		
	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.
14000	0.0097	0.109	0.991	0.0113	0.137	0.756	—	—	—
12000	0.0090	0.080	0.782	0.0114	0.101	0.612	0.0093	0.085	0.515
10000	0.0080	0.056	0.576	0.0107	0.069	0.471	0.0092	0.059	0.402
8000	0.0089	0.035	0.386	0.0113	0.045	0.325	0.0101	0.038	0.289
Average	0.0089			0.0112			0.0095		

B	508 deg. cent.			597 deg. cent.			659 dcg. eent.			700 deg. cent.		
	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.	$\beta \times 10^{10}$	Ed.	Hyst.
14000	—	—	—	—	—	—	—	—	—	—	—	—
12000	0.00804	0.076	0.373	0.0109	0.107	0.154	0.0120	0.108	0.083	—	—	—
10000	0.00865	0.053	0.313	0.0118	0.074	0.138	0.0133	0.083	0.064	0.0160	0.100	0.010
8000	0.00878	0.034	0.248	0.0129	0.048	0.117	0.0142	0.057	0.057	0.0175	0.070	0.011
Average	0.00849			0.0119								

The values of x determined in the same manner as for sample No. 2 were as follows:

B	47 deg. cent.	300 deg. cent.	402 deg. cent.	508 deg. cent.	597 deg. cent.	659 deg. cent.
8000	1.600	1.600	1.600	1.600	1.600	1.600
10000	1.604	1.602	1.597	1.586	1.574	1.574
12000	1.605	1.598	1.585	1.569	1.560	1.570
14000	1.606	1.596	——	——	——	——

An investigation was also made upon the permeability of this sample as it approached and came out of the non-magnetic state. This was done by keeping a constant magnetizing current of 2.5 amperes 60 cycles in the primary and noting the change of

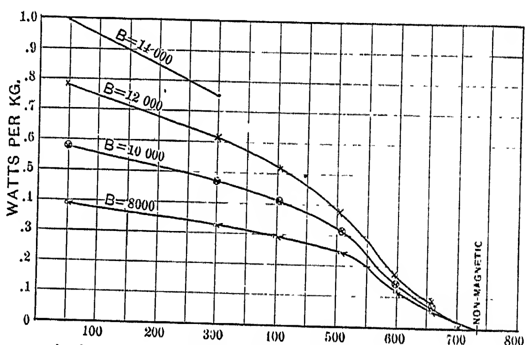


FIG. 7

induction as determined from the secondary voltage as the temperature changed. The results were as follows:

Heating		Cooling	
Induction	Temperature	Induction	Temperature
8200	702 deg. cent.	8280	707 deg.cent.
7460	715	7660	715
6010	727	6015	726
4660	732	4710	729
3550	735	3360	732
1610	737	1530	735
916	737	765	737
0	737	0	737

Direct Measurement of Hysteresis. As a check upon the above results, hysteresis loops were plotted at several inductions upon sample No. 2. The arrangement of the apparatus in this test is shown in Fig. 8.

The magnetizing force in the sample was determined from the expression $H=\frac{2\,S\,i}{10\,r}$ where S is the number of primary turns, i is the current in amperes and r is the mean radius of the test ring. For sample No. 2, $H=2.06\ i$. i was measured by the ammeter A in the primary circuit. Four German silver resistance frames with sliding contacts were used for varying the magnetizing current. A d'Arsonval galvanometer G was placed across the terminals of the secondary. A shunt was used with the galvanometer in order to keep the deflections within a suitable range and reduce the time of the cycle.

If a magnetizing force H is applied to the sample and is gradually reduced to zero by reducing the current at such a rate

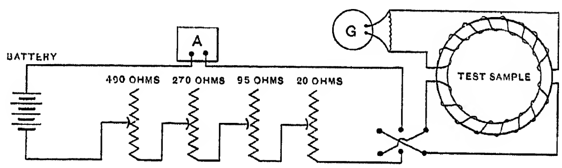


FIG. 8

as to keep a fairly constant deflection on the galvanometer and if the magnetizing current is then reversed and gradually increased until $-H$ is reached, then the average galvanometer deflection multiplied by the time required for the reversal is a measure of the total change of induction in the sample in passing from $+$H to $-H$. In these tests simultaneous readings upon the ammeter and the galvanometer were taken at 10-second intervals. If the galvanometer deflection varied, the average during the interval was recorded. In this case the sum of the galvanometer readings multiplied by 10 was the measure of the change of induction. The galvanometer was calibrated by means of a potentiometer and a standard cell, and one division of the galvanometer scale was found to equal 2.74×10^{-4} volt, so that the total change of induction equals

$$\frac{2.74\times10^{5}\times\text{sum of deflections}}{\text{number of secondary turns}}$$

and the induction per square centimeter in the sample corresponding to H was therefore:

$$B=\frac{2.74\times10^5\times\text{sum of deflections}}{2\times12.9\times156}=67.8\times\text{sum of deflections.}$$

It also will be readily seen that the change in induction due to the change in the magnetizing force between consecutive readings $=2\times67.8\times$galvanometer reading.

The method of plotting the hysteresis loop from a set of readings between $+H$ and $-H$ is then to take the sum of the galvanometer readings between these limits to determine B cor-

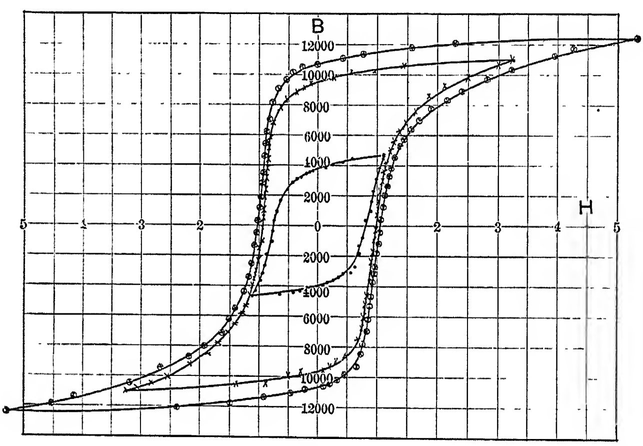


FIG. 9

responding to the maximum positive value of H. At the end of the first 10 seconds the ammeter reading will show a magnetizing force H_1 and the galvanometer reading will give the corresponding change in induction B_1. The actual induction in the sample due to H_1 will then equal $B-B_1$. Other points on the hysteresis loop will be found in the same way until $-B$ corresponding to the maximum negative value of H is reached. As a check upon the accuracy of the observations it is well to continue the test until the starting point is again reached, the sum of the positive galvanometer deflections should then be equal to the sum of the negative deflections.

It should be noted that this method of measuring hysteresis loops possesses a considerable advantage over the usual step by

step method with a ballistic galvanometer, in the fact that it is not necessary to predetermine the resistance steps as this is taken care of entirely by watching the galvanometer deflection. As far as the writer is aware this method has not previously been applied to small samples requiring laboratory instruments for the measurements. It was first suggested by Mr. C. F. Scott and developed by Mr. Scott and the writer for the purpose of determining the permeability of the nickel-steel field ring of the first large generator installed at Niagara Falls. The field ring itself was the test sample in that case and the magnetic flux was of such a magnitude that a voltmeter could be employed in the secondary circuit for the measurement of the induction.

Three hysteresis loops obtained by this method are shown in Fig. 9. Immediately after these were taken, measurements were made by the two-frequency method, and the values of the watts lost per kg. at 25 cycles determined by the two methods were as follows:

	Loss by direct measurement	Loss by two-frequency method
For B— 4650	0.306	0.282
" B—11000	1.16	1.22
" B—12400	1.595	1.55

The writer is indebted to Mr. Philander Norton for his valuable assistance in making the observations and in calculating results.

Discussion on "Effect of Temperature on the Hysteresis Loss on Sheet Steel", "Commercial Testing of Sheet Iron for Hysteresis", New York, April 14, 1911.

C. H. Sharp: It may not be amiss to consider very briefly some of the improvements in method and apparatus for magnetic testing and also some of the difficulties which are met with in this class of work.

Testing by the ballistic galvanometer method has been greatly simplified by the use of a long period D'Arsonval galvanometer as ballistic instrument in place of the old undamped moving needle galvanometer which made such a record for itself as a troublesome and time-wasting instrument. The D'Arsonval galvanometer is given any required degree of damping so that it may be used without a loss of time in bringing it to rest. It is calibrated by reference to a standard of mutual induction and its constant is expressed no longer as a ballistic constant, but rather in terms of line of force cut per centimeter throw. The long period is required not so much to enable the throws to be read with accuracy as to obviate the effects of magnetic viscosity in the specimen.

The errors involved in the use of yokes in testing straight specimens have been taken account of and yokes with compensating windings which carry sufficient current to overcome the magnetic reluctance of the yokes, joints, etc., have been devised and put into practical use.

The Picou permeameter, an instrument designed on this principle, has been found in our work to have a very limited range of usefulness and not to be a successful practical instrument. The investigations of the Bureau of Standards along these lines have been most thorough and painstaking and have resulted in the development at the Bureau of Standards of practical forms of compensated yokes wherewith really accurate permeability and hysteresis tests can be made with a reasonable expenditure of time.

Among instruments intended for giving a relatively quick determination of permeability curves and hysteresis loops, by substituting a more convenient device in place of the ballistic galvanometer, the Koepsel instrument has probably a predominate place. The compensation of the yoke reluctance in this instrument, however, is very imperfect and the results obtained for it require so much correction to take account of the unknown reluctance of the yoke, and of the joints, that it can hardly be considered as giving very accurate results in any work except in the comparison of samples of similar material.

Practically, not only the hysteresis loss but also the eddy current loss should be known. This fact leads directly to the wattmeter method of testing samples. If the iron is tested at the same induction with two different frequencies of the

alternating current or if it is tested with the same frequency but at two different values of the induction, the eddy current and hysteresis losses can be separated from each other. There is no practical difficulty in measuring the losses in even quite a small sample of iron if the proper instruments are available. The wattmeter used must be one which is accurate on low power factors. If the sample is quite a small one, some special sensitive wattmeter is required such as for instance, the suspended type, using a mirror and spot of light for reading. It is advisable to use a separate winding for the potential measurements as Professor MacLaren has done. Sometimes a third winding is put on which is connected to an electrostatic voltmeter. Under these conditions the electrostatic voltmeter indicates the total e.m.f. set up in the winding, and consequently the maximum induction; that is no correction is necessary for fall of potential in the windings, due to the voltmeter current. The temperature of the windings and of the sample should be accurately controlled and the temperature at which the losses are measured should be stated. This is very seldom done, but in as much as the eddy current loss must have the same temperature coefficient as the resistance temperature coefficient of the iron; namely about 0.5 per cent per degree, the necessity for stating the temperature is obvious. Inasmuch as the sample may tend to rise considerably in temperature during a test, it has been found in our work advisable, at any rate when working with small samples, to immerse the entire arrangement in an oil bath. Furthermore, if the temperature of the oil bath is kept at some definite value, as for instance 50 deg. cent. the losses are measured at a temperature comparable with the temperature which the iron will actually have in use. It would be advisable therefore that a standard temperature at which these tests are to be made should be agreed upon.

The test should be made with a sine wave form. This is required because the losses vary with the wave form. It is not sufficient simply to assume from the fact that the wave form of the generator is practically sinsuoidal, that the form factor, which enters directly into the computation of the maximum induction produced in the iron, is exactly 1.11. The actual form factor of the wave of e.m.f. set up in the iron should be investigated and its actual value determined. Any error in the determination of the form factor affects the value computed for the maximum induction by the same percentage, and consequently affects the value for the losses at a given induction by a considerably larger percentage. The form factor may be determined either from an actual plot of the wave, or by rectifying the wave by means of a commutator attached to the shaft of a synchronous motor, and comparing the value of the rectified e.m.f. as indicated by a permanent magnet voltmeter with the value of the alternating e.m.f. as measured by a dynamometer type of voltmeter containing no iron. In this arrangement it is not always easy to be sure

of perfect contact between the commutator and the brush, so that a good deal of care needs to be used, to avoid error from this cause.

The pieces from which the magnetic circuit is built up need to be carefully insulated from each other. The exact method of building a magnetic circuit does not seem to be a matter of great importance. In the Bureaus of Standards apparatus the joints at the corners of the magnetic square are more perfect than in the Epstein apparatus so commonly used in Germany. The result of this is that the wattmeter is used at a better power factor. In the Möllinger apparatus the samples are continuous, ring-shaped stampings and the windings are quickly put on by a special arrangement. This gives a more perfect magnetic circuit than either of the other forms, but requires a less economical form of stamping and gives practically the same results as the Epstein apparatus. Wild, in a recent paper before the Institution of Electrical Engineers, reported finding several per cent higher loss in the Bureau of Standards' style of magnetic square than in the Epstein style. He attributes this to the increased hysteresis in the corner pieces due to bending, and considers the results of the Epstein apparatus to represent more nearly the true values.

The question of the sample seems to be the most difficult one in connection with the wattmeter method of testing. In the Epstein apparatus 10 kilograms of iron are used. The quantity is so considerable and the individual pieces are of such size that the resultant sample can scarcely fail with proper selection, to be representative of the iron. Where smaller samples are used, the doubt increases as to the representative quality of the sample, and this seems to be the chief difficulty in the use of small samples for the wattmeter test.

Mr. Robinson's method presents the wattmeter test reduced to the greatest possible simplicity. The only question about it seems to be that of the size of the sample and in as much as Mr. Robinson has found it to give satisfactory results in the immense amount of work which he has done with it, and the results of which have been of the very greatest commercial importance, it is hardly open to doubt that as a workshop method his is a most excellent one.

Edwin F. Northrup: I have been interested in Professor MacLaren's paper on methods of hysteresis testing because of the importance of the subject, and also, for what the paper tells and suggests.

While I do not feel as competent to discuss methods of iron measurement as I would methods of electrical measurement, nevertheless I have some thoughts regarding the subject of the paper which may be worth expressing.

In addition to the losses in a transmission system which result from depreciation of the equipment there are two sources of loss which have received a searching study, namely, the

copper losses on the line and the iron losses in the generators and transformers. The control of the copper losses has become so good that it is not unreasonable to specify conductivities for the copper, or aluminum conductors, used to within a fraction of a per cent, and conductivity measurements can be made by a single observer with great rapidity to within a quarter of one per cent. Yet, without data at hand to confirm the suggestion, I should suppose that it is costing thousands of dollars to overcome unnecessary hysteresis losses, to hundreds of dollars spent in overcoming unnecessary copper losses. Severe specifications respecting the quality of conductor materials, in the present state of engineering development, can be made with much better justification than they can respecting the qualities of transformer irons and steels. This is in part due to the fact that conductivity measurements are so much more easily and precisely made than iron measurements. Any contribution, therefore, to our knowledge of practical methods for making iron measurements is welcome.

Iron measurements have directly in view a commercial end and in devising methods for making measurements one should work from the commercial view point. Laboratory precision, as applied to many electrical measurements, is of relatively small importance in making iron measurements as compared with simplicity, rapidity and the use of few observers.

Professor MacLaren presents us with two methods of testing iron, and with the first of these methods he obtains results which are very interesting. His first method, the wattmeter method is not new but his second method, the direct measurement of hysteresis, is, as far as I know, described in print for the first time. I have had the opportunity of examining the construction of his samples, the apparatus used in his tests, and myself have made a trial of his second method. I am convinced that his work was done with painstaking care and that all his statements are conservative. His construction of a furnace for regulating the temperature of the samples, I think is particularly well adapted to what it has to do.

The curves, giving the relation, between watts lost per kilogram of steel, and degrees centigrade, are interesting in the extreme. It would appear from these curves that a reduction in the hysteresis loss to one fourth its original value, by an elevation of temperature of some 500 deg., is a physical fact and one of much significance. It looks as if the molecules turn about under the directive force of the magnetic field with less friction as they become further separated by elevation of temperature. One should also expect considerable diminution in the eddy-current losses, with elevation of temperature, from the increase in the specific resistance of the iron. Referring to tables I, II, III, of the article we find this not to be true throughout the entire ranges of temperature used. In table I, for any given induction, say 10,000, we have the eddy-current loss, starting at 24 deg.

equal to 0.312 and falling at 390 deg. to 0.166, but then rising again at 535 deg. to 0.246 and continuing to rise at 708 deg. to 0.92. Sample No. 1 was thought to be defective in insulation, but there is no regular decrease beyond 597 deg. even in sample No. II, table II. If both the hysteresis loss and the eddy-current loss in transformers decidedly decreases with elevation of temperature, and if the decrease in loss should prove to exceed the increase in copper losses, and if the elevated temperature does not gradually diminish with time the permeability of the steel, it might actually result that transformers would show a total higher efficiency when run hot than when run cold. It is doubtful if experiment would justify this conclusion, but I suggest it as a research for some one, to make a prolonged test of the relative efficiencies of properly insulated transformers operated at, say 40 deg. temperature and 200 deg. temperature. It is not improbable that the insulation problem could be cared for with asbestos covered wire and some of the new insulating compounds.

The data at the bottom of page 548, in which Professor MacLaren finds that the curves, showing change in induction as the iron passes through the magnetic point, practically overlap, both for an increasing temperature and for a decreasing temperature, have, to my mind, an important physical significance. On many samples of steel tested by me, to determine their heating and cooling curves, I found that in all cases the recalescent point lay some 26 deg. or more below the decalescent point. In one low carbon steel the decalescent point was at 724.4 deg. C. and the recalescent point at 676.4 deg. C., In this case the two points were separated by 48 deg. In the case of a high carbon steel the decalescent point was at 728.4 deg. C. and the recalescent point at 702.4 deg. or a difference of 26 deg. Now, as iron or steel is supposed to lose its magnetism, when it passes through the decalescent point and to regain its magnetism when it passes through the recalescent point, it is quite remarkable that Professor MacLaren should find the induction on heating the sample to be 6010 at 727 deg., and to find the induction on cooling the sample to be 6015 at 726 deg., which is practically the same thing. Perhaps a sample of steel when under the influence of an alternating magnetomotive force will have its recalescent point and decalescent point located at the same temperature. This is worth a trial for the physicists.

Professor MacLaren's second method of the direct measurement of hysteresis has the very great advantages of being applicable to an extremely wide range of induction, of giving the data, for plotting the hysteresis loop, in about ten minutes, and of being, to a certain extent, self checking (as the sum of the deflections for change of induction in one direction must equal the sum of the deflections for an equal change of induction in the opposite direction). It has the disadvantage from a commercial standpoint of requiring from three to four observers. Then,

also, the reduction of the data and the plotting of the curves require considerable time. I believe the method could be made very much more rapid, as well as more accurate, by making it partly automatic.

It would be a simple matter to construct a recorder, whereby the galvanometer deflection would be recorded as a sinuous line upon a cylinder revolving uniformly with the time. The same recorder, or another one, could be made to record synchronously on another revolving cylinder, the change in the magnetizing force. From the two curves so drawn automatically, to a proper scale, the data could be taken for drawing the hysteresis loops. The delicacy of the galvanometer required would be no impediment to such automatic recording, as much more difficult problems, in the automatic recording of temperatures registered with very sensitive galvanometers, have been already solved commercially by myself and others.

It seems to me that progress in iron measurements should follow along the line of seeking greater rapidity in taking the data in methods of rapidly reducing the results, and in making automatic, processes now performed manually. To accomplish these results I can say with a certainty only requires capital and enterprise.

J. A. Capp: Mr. Robinson has described two sets of apparatus for measuring the hysteresis loss in sheet iron samples. A brief statement of about ten years' experience with the apparatus, using the bundle of 10 in. x $\frac{1}{2}$ in. strips, in the commercial testing of sheet iron may be of interest.

The first and most obvious use of the test method was in the inspection of raw material and its testing to determine whether or not it conformed with the standard established in the specifications. Consideration of the many points which have bearing upon the preparation of purchasing specifications soon indicated that such specifications must define the required chemical composition of the steel and its manipulation in the rolling mill. At the time when this work was begun, the rolling mills were generally not equipped to make tests to determine the magnetic quality of their product but they did understand the chemistry of the steel and, of course, had control over mill processes. Experience shows that relatively hard sheets can be punched with greater ease to a given degree of accuracy than softer or thoroughly annealed sheets. It had long been recognized that heat treatment has fully as great an influence upon the quality of the sheets as composition. The use of the relatively hard sheets immediately then requires that the final heat treatment be done by the purchaser and it is obvious that the manufacturer cannot be held accountable for the results of a treatment applied by the purchaser and over which the manufacturer can have no control.

The next, and what has since turned out to be the most important use of this convenient means of commercial testing

was the determining of the best treatment to apply to sheets to put them in a state having the maximum permeability with minimum hysteresis. This work was undertaken by selecting typical lots of steel from the standard commercial output of several manufacturers and from which lots of steel a very large number of 10 in. x ½ in. strips were cut. These strips well mixed, so as to be broadly representative of the lots from which they were taken, were made up into the one pound samples required in the hysteresis testing outfit. The hysteresis loss and permeability were determined for each of the samples and different samples were then carried through a long series of heat treatments, designed to indicate the influence of the rate of heating, the rate of cooling, the time the maximum temperature was maintained and of all the other variables which necessarily would enter into heat treatment of this character. In this series, thousands of samples were tested and the results when completed, indicated the desirable heat treatment of steels of the compositions and characters included in the lots selected.

This work provided the basis for the preparation of standard specifications which could be used by the purchasing department in their contracts for the sheet steel purchased. These specifications as already indicated, state the required composition of the steel and then define its manipulation by the producer, hence inspection testing substantially resolves itself into a matter of chemistry. But the question of proper mill manipulation still can be determined with reasonable dependence by the application of the prescribed heat treatment to the steel, when if the manipulation has been that specified, the hysteresis loss and permeability should equal at least a certain standard.

The necessity for heat treating the steel purchased at once requires that there be means of determining whether the prescription for heat treatment is actually being carried out in practice. The direct measurement of the temperatures used in the heat treatment is possible at least in certain parts of the furnace by pyrometers. It is obvious that a pyrometer can only measure the temperature of the particular point in the furnace at which it is placed and furthermore it is well understood that the indication of the pyrometer is more or less an average of the conditions surrounding its point of location. These considerations led to the use of hysteresis testing outfit as a check upon furnace work and an elaborate scheme was worked out for the exploration or the annealing furnaces by pyrometers and hysteresis test samples. Large numbers of the test samples were distributed throughout the annealing pots, as many as five or six hundred samples being used in one annealing heat. These samples had been taken from lots of material the history of which was thoroughly known and upon which the influence of varying heat treatment had been extensively studied. Hence the results obtained in the hysteresis outfit upon the test samples which had been distributed throughout the annealing pots

enabled us, with reasonable accuracy, to determine the distribution of temperature in the furnace and pointed to the way to correct inequalities in this distribution, and to establish a routine for the furnace manipulation. This routine, when followed, is expected to yield uniform results, but hysteresis test samples are regularly used as a check upon furnace work, and the heat treatment operations are controlled through the joint use of pyrometers and the hysteresis testing outfit. Samples are placed in the pots at what experience has shown are apt to be the hottest and the coldest parts, and when the test samples show results below normal, the punchings in the particular part of the pot represented by these poor samples may be sent back for re-annealing. Obviously the samples which are used in this way must be taken from stock which previous testing has shown will respond properly to the prescribed heat treatment, though it is but fair to say that almost no selection is required for this purpose, since the specifications provide a grade of steel which can be turned out by the producers with a highly satisfactory degree of regularity. Results are checked by tests upon samples taken from the actual punchings themselves and these confirm closely the results from the regular heat samples.

Still another commercial use may be made of a method of testing such as has been described. There are times when by reason of unusual service conditions, or because of unusually stringent specifications on the part of a customer, apparatus must be turned out which must be classed as special, because the core losses are required to be lower than in standard apparatus of similar design. In such circumstances, it is not always possible for the designing engineer to take care of the special necessities of the case in any other way than by the use of special material. Standard specifications provide material which, after proper heat treatment, may be expected not to exceed a certain maximum hysteresis loss. The average, however, is, of course, considerably below this maximum and there may be found exceptional lots which will run at a very low minimum. By having available a means of testing which requires but small quantities of material and the results from which can be quickly obtained, it is possible to go through stocks which could be used for the production of such special apparatus and select those particular lots which will run at or below the average. Advantage has been taken of this possibility in some of the rare cases where the designing engineers have been forced to require the use of specially selected material.

Mr. Robinson has discussed at some length the question of the general accuracy of the results obtained with the outfit using the 10 in. x $\frac{1}{2}$ in. specimens. Experience has shown that when a line of machines has been designed using material which has been tested extensively by this method and which machines after completion have been put through the usual tests, the designing engineer is provided with data upon which

he may determine within close limits the core loss of machines of new design. We were at one time able to determine from tests made on the 10 in. x ½ in. samples that the manufacturing processes of one of the sheet steel mills had gone astray. Had we not been able, at least with a very close approximation to accuracy, to make tests upon a large number of samples so as to determine that it was actually temporarily characteristic of the output of that mill that we could not get the expected results, we would have been forced to work in the dark and probably would not have been able to prevent the use of a good deal of poor material in commercial apparatus. We were able so to impress the mill representatives with the results shown them that they made an investigation only to find rather to their astonishment that a supposed improvement had been made in the process by a man in the mill who had not thought it necessary to bring the change to the notice of his superiors.

When the apparatus was first set up for use, there was some doubt whether readings could constantly be duplicated on the same samples. Therefore, a number of samples representing a wide range of results was tested and laid aside under lock and key. These were taken out at irregular intervals and tested for a period of some two or three years. The greatest variation found was not over one per cent which, of course, is considerably less than the normal variations to be expected in a large number of tests representing one particular lot of material.

The foregoing has shown that a very considerable commercial use is being made of the testing outfit described. This extensive use, however, is made possible only by reason of the speed with which results may be obtained and by the comparatively small weight of material which is required in the test. Mention has been made of the use of the method as a check upon the material received to indicate conformity with specifications, and as a check upon the heat treatment applied in the annealing furnaces, which check is accomplished not only by the testing of the samples which are prepared and placed at predetermined points in the annealing pots but also by tests upon samples punched from the material actually annealed. Tests of the samples are made not only before and after treatment, but also upon a considerable proportion of them after subsequent exposure to moderately elevated temperatures to determine the amount, if any, of increase in hysteresis due to what is commonly called aging. This together with experimental work, requires the testing of an average of about 600 samples per week. The samples are delivered to the laboratory in the form of loose strips 10 in. x ½ in. These must be assembled into the one pound bundles, the top strip of which is stamped with an identifying number. The bundles are weighed and the necessary data entered in a record book. The samples are then turned over to the furnace men by whom a record is delivered to the laboratory showing the location of the several samples in the various pots. This data is

added in the record book, together with the results of tests before and after heat treatment and aging. Results are then entered on a blank report form which is sent to the parties who must know the detailed results.

Mr. Robinson has briefly referred to the necessity for economy in the use of material where a large number of tests is to be made. This is obvious when it is considered that the test samples are not of suitable size or shape for productive use, and hence may become an item of expense worthy of consideration. Furthermore, room in annealing pots may not be taken up unduly by test samples without reduction of productive capacity, hence the test samples must be small in volume and of such shape that they may readily be placed in the annealing pots without interference with the regular production material. Special shearing devices have been provided for cutting the 10 in. x $\frac{1}{2}$ in. strips so that the waste of iron is at a minimum. We have stated that there are an average of 600 tests per week made and reported. Some of these tests are repeated on the same sample so that there are actually required about 500 samples or an equivalent number of pounds. Each sample consists of an average of 52 strips of fourteen mil iron. Hence, there are about 26,000 strips of iron handled per week in making up the samples. Obviously, if the sample were larger than that now used, the weight would be increased proportionately as well as the cost of material consumed, and labor of handling.

From all this, there may be formed an idea of the amount of labor involved in the testing and clerical work. Perhaps the best indication of the speed with which the work may be done is the statement that all of this work is carried on by two men who have time left to do the laboratory annealing experiments which are constantly in progress.

L. W. Chubb: The magnetic testing of sheet steel had been a very active subject for the last few years, especially during the development of the silicon steels. I have no formal notes on these papers to-night, but some points have come to my attention that I would like to ask some questions about. Is it not true that the use of windings of iron wire, referred to in Professor MacLaren's paper, is a source of error. If, when the temperature gets high, the permeability is very much reduced, excessive exciting current in the iron wire would cause distortions of the induced voltage and the flux in the sample. Such distortions would apparently lower the hysteresis loss and be caused by decreased permeability, even though there would be no decrease in the area of the true loop of the steel. It would seem as though the combined resistance and inductance of the iron winding would cause drops and distortions, resulting in hysteresis errors of several per cent. No data has been given for the high induction points at high temperatures, and I therefore assume that reduction of permeability was a limiting feature. I would like to ask Professor MacLaren if any results

were taken showing the relation between permeability and temperature.

Mr. Robinson's paper treats of testing methods that need to be carried on very extensively in a large commercial factory. In our work we use a single method with a sample which is between the one pound sample and the standard Epstein sample described in the paper.

In certain work it is the custom to use steel without annealing after punching, and the sample consisting of small strips 10 in. x ½ in. does not give a representative result for the steel. The variations in a commercial sheet of steel are as great within the sheet as between separate sheets, and therefore the test with the small sample is not satisfactory, not only because of the damage due to cutting small strips, but also because such a sample does not sufficiently cover the area of a commercial sheet. To get a representative one-pound sample from a sheet or lot of steel, it is necessary to resort to some complicated scheme of cutting, which is laborious and wasteful of material.

Our Epstein apparatus uses samples of fifteen pounds of strips 15½ in. long by 1³⁄₁₆ in. wide. The results obtained with the 15-pound sample check results obtained with the standard Epstein samples. Several details in the method are different. The first I will mention is the use of a secondary winding. In our apparatus we take the potential for the wattmeter coil and for the voltmeter directly over the exciting winding. This includes in the wattmeter reading the $I^2 R$ loss in the windings. The voltage drop in the winding also tends to reduce the measured core loss.

At first sight it would seem inadvisable to introduce such errors in the testing method, but we have found by very careful ballistic exploration of the Epstein sample that the error due to the leakage at the corners is greater than the resultant error caused by the $I^2 R$ loss and the $I R$ drop in the winding. Since resultant copper error and the leakage error are in the opposite direction, and are both functions of the permeability of the steel, they will always cancel the effect of each other to a certain extent, and when the coils are properly proportioned the method will give better results than when a secondary winding is used.

Dr. Sharp brought up the point that the results in Professor MacLaren's paper given by the ballistic method and by the wattmeter method do not agree exactly. Mr. Robinson shows in his paper a rather close agreement between the two. Many researches on the comparison of the wattmeter and the ballistic methods have generally shown the ballistic results to be lower than the hysteresis part of the wattmeter results, which seems to be correct.

When flux grows in a lamination of finite thickness the eddy currents will cause a skin flux, and the induction will not grow with uniform rate throughout the lamination. This will result in a variable maximum induction and increased hysteresis loss.

Work done by Dr. Lloyd shows that only when the laminating of the steel is very fine will there be a close agreement between the hysteresis loop taken ballistically and the hysteresis per cycle, taken by the wattmeter test. I believe that the reason Mr. Robinson's results check as close as they do is because he takes his voltage from a secondary winding, and the leakage error causes a reduction in the measured loss.

Mr. Robinson states in the paper that the flux variations due to leakage amount to not more than eight per cent. I assume that he means variation at an induction of 10,000 lines. Exploration of the sample under direct current excitation has shown that the leakage at the corners is very much greater and the resultant error to be more than one per cent. The design of Mr. Robinson's apparatus, the Epstein apparatus, is novel, and I believe it is a very fine scheme. We use corner blocks and clamps similar to those shown on the Epstein set in Fig. 4.

Repeated tests have shown variations between the results obtained by different operators, while the same operator can test a sample repeatedly and get the same result. The variations were found to be caused by differences in clamping the corners and pounding the corner blocks. I believe the clamping scheme shown in Fig. 5 is a great improvement over the usual Epstein corner blocks, and will do a great deal toward eliminating the personal equation in testing with a given set of apparatus. The other advantages mentioned in the paper are also of great importance, and make the adoption of the new clamping method seem advisable for standard Epstein apparatus.

R. B. Treat: A comparison of the two pieces of apparatus indicates that testing by means of the one pound sample is economical only for sheet makers or users who require many tests per week. The 10 kilogram apparatus is the more economical for a few tests per week, or infrequent tests, because of the use of commercial instruments which are available for other tests and are returnable to the makers for repairs and good results can be gotten by the average operator. The one pound apparatus requires the maintenance in usable condition of infrequently used special instruments, a thing very annoying and expensive. The high cost of material in the 10 kilogram samples is a disadvantage, but is to be preferred to the special instruments of the one pound apparatus.

Mr. Robinson takes it for granted that we are familiar with many of the minor details involved in the tests. It may be well to mention the importance of a few of them. Users of steel find it necessary to check the quality of incoming material with the supplier's guarantee and with specification. The samples should be sheared but unannealed, unless there is an agreement with the supplier that he will accept annealed tests. Ordinarily the purchaser of sheet steel must be able to test the suppiled material without subjecting it to any questionable process, such as punching or annealing. Some so-called annealing is ruinous to the material.

Users of steel require also to know the properties of the material when incorporated in the finished apparatus. For this information the samples may be either sheared or punched, but should receive an annealing identical to the usual manufacturing process.

Mr. Robinson chooses a width of sample such that the effect of shearing is small, but while small in a sheared sample it may be very large in a punched sample, for these reasons: Shearing must be a clean cut, or there will be no cut at all, while a punch may cut cleanly, or it may mechanically disturb the metal for a considerable distance from the edge of the sample.

Samples can be japanned or shellac coated at a very small cost, so it is advisable to do this and thus minimize the effect of fins on the edges. Japanning increases the weight of the sample about one-half of one per cent, depending upon the thickness of the coat. Annealing may change the specific gravity of the sample, under some conditions it increases the weight about two-tenths per cent both dependent upon the exposure of the sample to the annealing heat.

It would be well to settle upon a method of determining the cross-section of the sample, and consequently the value of " B ". This should be calculated from the weight and the longest dimension, for the percentage of error in taking this dimension is least of all.

It is very unreliable to micrometer individual sheets or even a squeezed pack.

Area determined by weight, and that by linear dimensions, may differ by ten per cent. The weight per cubic inch of silicon steel is about 0.271 lb. and common steel is about 0.275 lb., one and one-half per cent difference.

The butt joint with its paper insulation, has the advantage over the lap joint in that the flux is less likely to pass through the sheets at the joint, which might set up local eddy currents. The butt joint however causes leakage which has the effect of apparent higher core loss. This is easily demonstrated by successive tests with varying insulation in the joints and has been discussed by the Washington Bureau of Standards.

The Magnetic Committee of The American Society for Testing Materials has given the subject of sheet steel tests considerable study and we may hope it will soon settle upon a standard method for the use of both the maker and user of electrical sheets.

W. J. Wooldridge: Several speakers in referring to Prof. MacLaren's paper have spoken of the probable errors due to the use of iron wire for winding. The paper as a whole seems to fill in a gap in our knowledge in regard to steel.

It would perhaps be interesting to bring to your attention again the fact brought out by Ewing in his book on Magnetic Induction of Iron and other Metals, in which he points out that the permeability at very low inductions increases with increasing

temperature up to 775° C. and then decreases very suddenly between 775 and 786 deg. cent. At medium intensities that is less marked, while at high intensities the permeability falls off continuously, it does not increase as it does at low intensity—but falls off continuously, and falls off more rapidly at the end. In this connection it has been a question in my mind, and the minds of several people I have talked with from time to time, as to whether there was really some relation between hysteresis loss of high density and permeability. We know that at low densities there is no such relation, because with an alloyed steel, the permeability at very low densities is very much better than in standard iron, but these permeabilities cross somewhere about 12,000 B, if I remember rightly, and it has been a question whether on densities over that there is or is not some relation between the hysteresis and the permeability. The results of this test would apparently show that there is no such relation, and therefore this paper fills a gap on a point concerning which we did not have definite knowledge before.

As near as I can make out in table III, the logarithmic relation between the hysteresis loss at various densities does not follow the 1.6 law. One of the speakers has mentioned that the eddy current loss does not vary as everybody supposed it would, *viz.*, that it should be stated as varying inversely as the specific resistance. The eddy loss in ordinary iron, at normal densities and frequencies is, roughly, 30 to 35 per cent. Silicon steel has between four and five times the specific resistance of ordinary iron, but the eddy loss is reduced only to 18 or 20 per cent, which does not follow at all the supposed law in regard to specific resistance.

W. R. Whitney: In the Research Laboratory we have found, after considerable experimental work, that it is desirable to employ as small samples as practicable for test. The reasons are almost obvious. Small samples of new material are usually much easier to obtain than large ones. Experimental work on these samples, such as heat treatments, compression and bending experiments, etc., can be more easily performed than on large samples. A relatively large number of separate samples can be taken from a small sheet of iron, and by taking the average of measurements on many small samples, results are sometimes obtained which would be concealed by the measurement of the hysteresis of the same quantity of iron in a single sample. For this reason we have often used a Ewing tester, where separate measurements were made on each ounce of iron, and have followed up the leads opened by such tests, by means of the standard factory one pound samples. In experimental work it is very important that all unnecessary barriers be removed from the way of quick and easy production of samples. It is preferable if the iron can be cut, annealed and tested in the same room and by one man.

Samples must also be capable of quick and simple measure-

ment, and finally, large numbers of the identical tested samples should be kept on hand for later reference.

This is all very easy with one ounce samples, but the Ewing tester, in our hands, is little better than a qualitative instrument, so that we have always referred to one pound samples for accurate conclusions. Such samples are also still small enough so that care and storage of them is not a serious matter. When the tests are made on twenty-two pound samples, it becomes evident that even the cost of the samples themselves is a factor where much testing is to be done. To make many tests in one day or to store identical samples in any quantity becomes a burden, if they are too heavy.

C. J. Fechheimer: The methods which have been described this evening for testing iron are applicable principally to transformers, in which the distribution of flux is very similar to that which obtains in the samples. They cannot, however, be used directly in dynamos or motors because in these there are heavy pulsations of flux and the distribution of flux in the core is by no means uniform and is quite different from that which we generally assume. The rapid change of flux which takes place when the edges of the poles pass under the armature teeth (or the armature teeth pass under the poles, whichever the case may be) also materially affects the loss occurring in the teeth. The result is that the core loss is two or three times as great as we would determine ordinarily by the constants obtained from transformer tests.

One of the speakers said this evening that the tests made in the factory on samples of new grades of steel are used for laying out a new line of machines. This, I believe, should be the case to a limited extent only, but I would be inclined to question it, because the transformer tests are not necessarily indications of what may be expected when the same steel is used in the armature cores of generators or motors.

For example, we know that while silicon steel has an eddy current loss, measured by means of transformer tests, which is considerably less than that of common steel and has also a slightly lower hysteresis loss, yet this steel does not have any appreciably less loss in generators or motors than the common steel. I questioned the results of the tests for sometime and had them repeated and was finally convinced when the temperatures indicated that the core loss as measured was correct.

There were six turbo generators of a certain size built, three with silicon steel and three with common steel, and the loss seemed to be about the same in all cases. There was, of course, some slight variation, but this variation was not any greater than that which usually occurs in duplicate machines built with the same quality of iron. I have never been able to account for this discrepancy and I should very much like to have an expression of opinion from some of the members to help clear this up.

Then there is another point which we find in practice does not

agree with theory. We usually assume, and without doubt correctly, that the eddy current loss varies with the square of the frequency and the square of the induction density. The hysteresis loss varies with the first power of the frequency and approximately with the 1.6 power of the density. However, I have found that the total core loss in machines varies from 1.9 to 2.2 power of the density, which would indicate that all the loss is due to eddy currents. Nevertheless when we compare the loss at different frequencies on the same machine we find that the loss is proportional to about the 1.4 power of the frequency, which would indicate that a great deal of the loss is due to hysteresis. This is another discrepancy for which I have never been able to account.

I should like to ask Professor MacLaren whether the iron did not age when starting with 25 cycles, repeating the tests at 60 cycles and then going back to 25 cycles. It would seem that the alternate heating and cooling of the samples causes the constants for the losses to be affected; that is, the iron would have aged.

C. A. Adams: At the recent mid-year convention at Schenectady, Mr. W. J. Wooldridge presented experimental data showing that the exponent of "B" in the Steinmetz formula for hysteresis loss was not a constant for modern silicon steels, but varied from about 1.5 at low densities up to 2.5 or more at high densities. The results of Prof. MacLaren's experiments seem to show that up to the highest density used by him, the exponent was 1.6 and practically constant throughout.

It is certainly very desirable that this apparent discrepancy be explained, for if both exponent and coefficient vary over a wide range, the Steinmetz law is not applicable to silicon steels.

W. S. Franklin: If the engineers concerned in making measurements would make a distinction between and use two distinctly different words for the two classes of errors, it would help us very much in regard to discussions of measurements of such things as hysteresis loss in iron. There are two distinct kinds of errors which physicists recognize, namely, errors due to the wabbling of the measuring instrument, and errors due to the inherent lack of constancy or definiteness of the thing you measure; and I think we should call the first of these errors, speaking of the probable error of a set of observations; that is, the things which are inherent in our methods and instruments, and the other things we should call departures. We could speak of "probable departures", etc. Take, for example, the main load factor of the consumer of electric lights who has fifty lights installed. We will say that the main load factor of that kind of a customer is 60 per cent. Now, as a matter of fact, there are enormous departures from that. If you were to take a large number of individual cases, you could determine what the probable departure is, for that probable use, if used in the same sense as we use probable errors. I wish we could get into the

habit of distinguishing clearly these two kinds of errors which enter into numerical measurements; one is external error and the other is internal error, and we might call one " error " and the other " departure ".

Malcolm MacLaren: In answering Mr. Sharp's question, regarding the use of iron wire, I would say that that was taken as a matter of convenience. It did not seem as though copper would be suitable to stand the high temperatures, and iron was the most convenient substitute. The wire was about one-sixteenth of an inch away from the sample, No. 18 wire used, the turns being spaced about one-eighth of an in. apart, so that with the large cross section of the sample it would seem that the error due to the additional iron in the wire would not be considerable. If extreme accuracy was aimed at, it would be probably better to use some other material such as nickel.

As to the ease of manipulating the apparatus in making the loop, I believe that it will be found that taking men who have not made loops before, they will find it much easier to accommodate themselves to this manipulation of the resistance than to making the observations with the ballistic step by step method. As an indication of the flexibility of the method we recently took loops varying from an induction of about 200 B up to about 14,000 B, in which the only change required was to vary the resistance in the galvanometer circuit, so as not to take too many points in tracing the loop through its cycle.

As to the lack of agreement in the measurements by the loop method and the two-frequency method, I can not explain slight discrepancies that occur except to say that at the lowest induction where the greatest discrepancy occurs the wattmeter deflection was too small to read accurately. I believe that the results presented by Mr. Robinson this evening are certainly a sufficient justification for the use of the two-frequency method in making such measurements.

Dr. Northrup speaks of the number of observers required to make the loop measurements. The loops presented in the paper were taken with two observers, it is a little easier, however, to have three, one to take the time, and read the ammeter, one to change the resistance, and the third to read the galvanometer.

Mr. Chubb speaks of the losses that would occur in the use of iron wire, but I think these have been largely eliminated by the use of the second coil which avoids the necessity of correcting for the $I^2 R$ loss and for the $I R$ drop. In addition, the currents were kept very low throughout the experiment, so that the distorting effect was small.

With regard to the change in permeability, this was not observed with any particular care. It was noted, however, that the change at the higher inductions was very small, until the higher temperatures were reached. Above 650 or 700 deg. cent., the permeability fell off very fast.

In reference to Mr. Fechheimer's question regarding the

method of making the measurements, the temperature was not allowed to fall at any time during the measurements, it was simply held constant for a sufficient time to take a set of readings, first at 25 cycles, then at 60 cycles, and then a few check readings at 25 cycles, so that the check readings would generally be taken less than ten minutes later the original readings. The sample was then allowed to heat up to the next point.

With reference to Dr. M. G. Lloyd's method of deriving values for the exponent of B in the expression for hysteresis loss, $w = a\, B^x$ I would say that the usually accepted interpretation of this expression is that the hysteresis loss in any magnetic material may be represented by a *constant* multiplied by the induction raised to an unknown power. If however the exponents given by Dr. Lloyd be used for the determination of a its value is found to be variable even with constant temperature. For example, using his figures in Table II for 218 deg. cent. a varies from 0.635×10^{6} to 1.49×10^{-8}. These revised tables which he presents appear therefore to have no physical significance. My reason for taking 1.6 as the value of the exponent at the lower inductions was that these samples were admittedly not as advantageously designed for obtaining extreme accuracy as would have been possible if the windings had not been arranged to stand temperature up to 800 deg. cent. and numerous other investigators had obtained this value for ordinary steel at inductions near 6000 B. Also the results that had been published upon silicon steel while not entirely convincing indicated that this value of 1.6 was correct for inductions near 8000 B.

With regard to the possible effect of eddy currents in the determination of the hysteresis loop I would call attention to the fact that the samples were well laminated and that the time of reversal was over five minutes so that the eddy current could not be large. It was possible however to detect their presence and estimate their effect by holding the magnetizing current constant for a few moments during a reversal and noting the galvanometer deflection. The correction due to this cause could not well amount to more than the width of the line bounding the loop.

L. T. Robinson: With reference to the points that have been brought up about the variation of the hysteresis exponent, it was certainly very interesting to see that Professor MacLaren got the original 1.6 power results, whereas some of the rest of us have got something quite different. Whether the explanation is that which Mr. Chubb gave, that there may be certain irregularities in the tests which Professor MacLaren made, and we are right, or that the 1.6 is right and we are wrong, I do not know, but I think that is something that perhaps can be straightened out within a short time, at least I hope so. I have a great many results, and I am trying to work them up now and see if I can make anything out of them.

About the ballistic method, and the agreement, etc., between

the two methods of measurement, I think I covered that in a fair way in my paper. I do not know whether it should agree, or whether it should not agree. There are so many things about the behavior of iron in magnetic fields that we do not know, that I do not think we should be too positive about our statements. I am satisfied to say that we usually have looked on the ballistic method as a good way to make the test. It was the standard method, and in developing another method we simply looked back to the old method to see how it agreed. There is a fairly good agreement, whether it means anything or not, I do not want to say. I hope it does, but we are not by any means sure of it, until such time as we can explain some of the vagaries with reference to the separation for eddy currents at different densities. The whole thing is founded on certain assumptions, some of it I hope is true. They all of necessity cannot be true. If you start in to discuss the whole subject and proceed to the final analysis along known lines, you cannot go very far. You assume that the eddy current loss varies as the square of the frequency. When you say that you say that it varies as the square of the voltage produced. When you say that it varies as the square of the density, you say the same thing, but still when you try to separate using various densities, it does not work. You cannot separate by change in density, although you can separate and get a straight line by changing frequency. Whether the fact that you get the straight lines means that you get the correct result or not, I think we can by no means be sure we are correct in saying. There is an opportunity for something to be said about this subject that has some definiteness about it that our present statements must lack, because of our want of absolute knowledge.

With reference to the long period D'Arsonval galvanometer, with considerable damping, old and new are only comparative words, I would say that we have used such an arrangement since 1898, to the best of my recollection, and I believe it to be good.

The Koepsel apparatus referred to is perhaps not directly connected with the subject matter of the evening.

I believe that it was brought out first in this country and published in the *Electrical World* some time in 1894. It is said to have been brought out sooner than that by the one whose name is now applied to it—but I think it was not published until some time after.

With reference to using insulation between the sheets, I think it is not necessary to insulate alloy iron but it may be necessary to insulate standard sheets.

I believe Dr. Sharp spoke of the disagreement between tests made by another method and by the apparatus that has been developed by the Bureau. My remarks on the elegance of that method were based almost entirely on the results that were obtained with it regardless of the comparison with other results —that is, it seems to be very good, because they get very nice

separations, and the things that vary more in other apparatus seem to vary less in it, and therefore I thought it was very good.

I think the matter of the standard sample has been quite generally referred to as being desirable. I was much interested in Dr. Northrup's remarks about the transformer running at 200 deg. cent.—we may have something like that some time, but the most interesting thing is what would he use for the insulation. That information is somewhat incomplete.

With reference to Dr. Franklin's remarks about errors and departures, I think that is a very good distinction, but it is hard to tell which is which. You do not get anything just right—sometimes you know you are wrong, but do not know whether it is an error or a departure.

With reference to Mr. Chubb's remarks, there is nothing more than a slight difference of opinion on what seems to be a minor point. I appreciate the fact that results can be obtained accurately by the method that he prefers. I may be wrong in thinking so, but it seems to me it is better to do something that is more generally applicable than to choose some arrangement for matching one error against another in a specific device. However, the specific point brought up as it relates to any apparatus except that described in the paper I have not covered experimentally, and cannot, therefore, be very definite in expressing an opinion on it at this time.

With reference to Mr. Fechheimer's remarks, it is interesting to know that some one has found some things that he cannot explain. We have been finding them right along, and it would be very easy to write a paper on the things about iron that you have tried and seen, and could not explain.

Henry Pikler: We are engineers, ultimately interested in the performance of sheet steel in the finished apparatus. If different makes of electrical machinery were built of exactly the same quality of sheet steel, we would find that the total iron loss per pound of sheet steel in these machines would not be the same, although the magnetic densities and frequencies are kept the same. This is due to differences in the design and construction between the electrical machinery of the various makers. In other words, if a given quality of sheet steel be used for building the transformers of makers " A ", " B " and " C ", we would find that the total watts loss per pound, at the same magnetic density and frequency, would be different in these three transformers. If instead of transformers we consider generators or induction motors, we would find that these differences would be much greater.

From this it follows that in order to foretell the total watts loss in the finished electrical apparatus, it is not sufficient to know only the core loss watts per pound in a sample of sheet steel tested by some standard method; the figure obtained by the standard method must be multiplied by a coefficient.

The difficulty lies in establishing a method of testing samples which can be used as a standard. I wish to emphasize that, for the reasons pointed out above, I do not consider that it is of primary importance at all that by the standard method physically accurate core loss watts per pound may be determined, but that by using this standard we should always get exactly the same result, whether the test is made by Peter, or by Paul, in the United States, in Japan, or in Germany. I would go even further and state that it is not a core loss—that is, a watt loss measurement—which is necessarily the criterion of the quality of the steel. To illustrate my point by a drastic example, I mean that if for instance a certain sample of steel, under the conditions created by the standard method, be struck and it vibrates say so many times per second and between this number of vibrations and the total watts loss there is a definite relation and finally *this* standard method can be exactly duplicated everywhere and at any time for the purpose of obtaining uniform results, then this method is more desirable than one which is based on watt measurements and gives not so uniform a result.

Probably the most important function of a standard method is to establish a basis in the transactions between the purchaser and supplier of sheet steel which excludes any chance of dispute. It is my opinion that there is a greater necessity for establishing a standard to this effect, one that gives uniformly correct results within say 2 per cent than to have this method for the purpose of enabling the designer to predict the core loss in his machine within that limit. Because I consider the uniformity of the results the most important, I naturally do not favor the introduction of any element into the standard method which is liable to introduce variations. For this reason I am very strongly opposed to any method of testing iron for the above purposes for core loss where the magnetic circuit of the test piece is broken by joints of any kind.

In reference to several remarks and questions brought up in connection with "core loss", which pointed out that the core loss of induction motors or turbo generators, etc., cannot be predicted, and furthermore the relations between watts, magnetic density and frequency do not follow the law given by the equation $W = M\ (B \backsim)^2 + N B^{1.6} \backsim$, I wish to give my opinion as follows:

In order to investigate these problems the engineer must become a physicist. Unfortunately, according to my observation, very few become such in their investigations. One of the most fundamental principles of physical investigation consists in attacking the problem step by step and these steps should be extremely small. A phenomenon, as it appears to us at first glance, is in reality a complexity of very many phenomena and we will not be able to understand the whole if we fail to recognize the details.

Take the simplest electromagnetic apparatus, the trans-

former. There the engineer assumes a uniform flux density as the underlying basis of his calculations, derived from the terminal voltage, frequency, number of turns and the dimensions of the core. The truth, however, is that in any commercial transformers, even with the best magnetic joints, such is not the case. The magnetic flux is the densest at the magnetic center, which is the center of the magnetizing winding and there the volts per turn are also the greatest. In either direction, away from this center, the density of the magnetic flux, and with it the induced electromotive force per turn of the winding, will diminish. Whereas in the neighborhood of the magnetic center the lines of force travel in the same direction as is the direction of the "mechanical" magnetic circuit in that region, in the neighborhood of the joints there will be many lines of force which will depart from the steel and will cut it transversely. Right at the joints this transverse cutting of the plates by the lines of force leaving them will be a maximum. This will introduce additional losses in the steel, mainly eddy losses, the magnitude of which depends upon the perfectness of the joint and the distribution of the winding over the core.

In considering, instead of a closed magnetic circuit of a transformer, the magnetic circuit of a generator or motor, we find the situation much more complicated. In these machines the irregular distribution of the magnetic flux is established even on purpose (low regulation, small slip, etc.). In these machines the transverse cutting of the core plates by the magnetic flux is very greatly pronounced. It is therefore a great mistake to expect to derive any conclusions as to core loss watts from measurements based on conditions where the magnetic flux travel in the direction of the mechanical magnetic circuit. Before trying to establish a relation between watts core loss and magnetic density derived from impressed or induced e.m.fs., turns and frequency, it is of primary importance to investigate the geometrical configuration of the path of the magnetic flux. This can be done either by exploring coils, or even by simple reasoning, based on experience, going step by step over the entire magnetic circuit and predicting the probable path of magnetism in order to get the geometrical configuration of the lines of force.

When we look at magnetic circuits, flux densities and core losses in this light, I think we shall be surprised to hear anybody expect a connection between core loss and magnetic density as derived from volts impressed, turns, etc.

M. G. Lloyd: It is highly desirable that some method of measuring hysteresis suitable for commercial conditions should be standardized in this country, for the convenience of manufacturers and buyers. The American Institute of Electrical Engineers could well take the initiative in this matter, as has been done by its sister society in Germany. There the Epstein method has been adopted and seems to give general satisfaction,

the standard test being at 50 cycles and 10,000 gausses. Perhaps the details of the Epstein method could be revised so as to be more acceptable in this country, but its predominant features should be retained for a standard comparison method. Where shop conditions make other methods desirable, they can of course be used, the standard method being resorted to only for occasional comparisons, and to check up results against those obtained by outside parties. The more accurate methods available by the use of properly proportioned rings or such apparatus as that in vogue at the Bureau of Standards are more especially suitable to investigations aimed at a correct value of the physical constants, and similar tests where accuracy is more important than economy in time, in materials or in the necessary apparatus. It is important, however, that any method adopted as a commercial standard should use a specimen of such dimensions that the hardening effect of the cut edges is small, since it is not always feasible to anneal after cutting, and indeed, unless annealing can also be standardized (a difficult matter), results obtained by different observers at different places would not be comparable. It is well recognized that the process of annealing is quite as important a factor in determining the properties of the material as any other factor involved. It is desirable also that the method should be adapted to the use of portable measuring instruments. This requires the use of a large sample, and it suggests the use of a good magnetic circuit in order to keep a fairly high power-factor. The Epstein method seems to have best met conditions generally found, but where it is necessary to make a large number of determinations in a short time, such a method as that described by Mr. Robinson is decidedly superior for the workshop. It gives comparative values with sufficient accuracy and has the advantage of using less time and material.

It is to be regretted that Mr. Robinson has said nothing about the application of his method to silicon-steel. Silicon-steel is usually used at higher flux densities than ordinary steel, and at the higher flux densities it requires a much larger magnetizing current, making a lower power-factor. In Mr. Robinson's method the magnetizing current must be large enough to induce the flux at the center of the specimen, and this may be 40 per cent higher than the nominal value of flux. The conditions are therefore much less favorable with silicon-steel than with ordinary steel.

The paper by Professor MacLaren is of great interest in showing the manner in which hysteresis varies with temperature. Caution should be observed, however, in attaching too much weight to the accuracy of his measurements. When the form-factor is not determined in the wattmeter method the results must be viewed with suspicion. Evidently the form-factor was not determined in these experiments. Even supposing that the voltage wave of the generator was sinusoidal, it is not likely

that the secondary electromotive force, whose form-factor enters into the computation of flux density, would have the assumed value. This is especially true since iron wire was used in the magnetizing coil and its resistance was probably high therefore, and moreover variable with temperature. Since the voltage used and the resistance of this winding are not given, it is impossible to judge of the amount of distortion probably present.

The values given for the exponents which represent the power of flux density which is proportional to the hysteresis are very misleading. In the first place they depend upon the assumption of 1.6 for one condition, and a computation based on this value for the other conditions. Moreover a very undesirable method has been used in making the computation. As a matter of fact the exponents vary through a wide range, from values less than unity to as high as 1.99, as will be seen in the accompanying tables, which have been computed for specimens two and three. In fact, at a temperature of 700 deg. the value is actually negative for silicon-steel, since it is to be observed that the hysteresis found at 8,000 gausses is greater than the value found at 10,000 gausses.

Professor MacLaren has computed his values by assuming 1.6 at the lowest flux density and used this value to determine the constant a, and the resulting value for a is used in computing the exponents for all other flux densities. In the tables which I have computed the exponent is found by means of the equation

$$x = \frac{\log w_1 - \log w_2}{\log B_1 - \log B_2}$$

and the value of the exponent therefore depends only upon the values found for the hysteresis at two values of flux density and the coefficient a is assumed to be constant only between these two points.

In the tables each value applies to the range of flux density between the value which it is opposite and the next preceding value. It will be seen from these tables that there is no regular variation in the value of the exponent, except that for silicon-steel at all but the highest temperatures the exponent decreases with increasing flux density. This result is in contradiction to most of the other experiments which have been made; most observers have found it to vary in the opposite direction. Reference may be made, for instance, to the paper by Mr. Wooldridge, at the Schenectady convention. As experience in this work has shown me what large errors may be produced in the result by small variations in the form-factor, it seems likely that these results are not very accurate and they are principally valuable in showing the general trend of hysteresis loss with temperature. In this connection it should be remembered, too, that at high flux densities the permeability decreases with increasing tempera-

ture. The magnetizing current would therefore increase and at the same time the resistance of the magnetizing circuit is increasing, so that the distortion would increase at a rapid rate.

The table given in the paper, showing the variation in induction with change in magnetizing current near the recalescence point, is chiefly valuable in showing the great rapidity of variation in that region. The differences found with ascending and descending temperatures are not significant. The two curves start very sharply at the same temperature of 737 deg. and cross at about 721 deg. An error in the measurement of temperature of three deg. would account for any difference found between these points. Since the variation of permeability with temperature is very different for different magnetizing forces, it is necessary to use a wide range of magnetizing forces to make such experiments of much value.

It is interesting to observe that the method used by Professor MacLaren for hysteresis loops can be used with small samples, as it has been generally supposed that this method was only applicable to cases in which the cross-section of the material, and consequently the flux, was very large. This method can hardly be claimed to have the accuracy, however, of the step-by-step method. Since the continuous change in flux will induce eddy currents which continue during the entire half loop, and since they oppose the main magnetizing field, the observed value of H will be too large. The extreme points of the loop will be correctly found, since the current becomes constant at these two points, but in between them the loop will be broadened, and the value for hysteresis will be too large. The result is similar to that found by the wattmeter method in a case where the eddy currents are small and are neglected. It is to be noted that in two of the three cases given, the loss is larger by this method than by the two-frequency method, although in the third case it is smaller by five per cent.

Dr. Sharp has called attention to the recent paper in the PROCEEDINGS of the Institution of Electrical Engineers in which the method used at the Bureau of Standards was reported to give results too high. I should like to call attention to the fact that the comparison was not made with the Epstein method, but with a different method whose accuracy was entirely unknown, although it was used as a standard of comparison. The only value of that research is in showing the differences found in the two methods.

It is sometimes wondered by those designing and testing electric machinery that the values of the exponents of flux density which are found in laboratory experiments, or computed on theoretical grounds, do not apply in practice. It would really be more wonderful if they did. Such an exponent as 2.0 for eddy currents, for instance, is computed on the assumption of uniform density in one definite direction in a sheet of infinite width. In dynamo and motor cores none of these conditions

are fulfilled, and even in transformer cores we do not have uniform flux density. The demagnetizing effect of the eddy currents makes the flux less at the center than near the surface. With increasing flux density or increasing frequency this effect is intensified and results in the eddy currents increasing at a less rate than the square of either of these quantities. As shown in Mr. Wooldridge's paper at the recent Schenectady convention, the exponent for eddy currents is actually found to decrease with increasing flux density, and such a decrease is qualitatively explained by the above consideration. It must be remembered, however, in connection with the determination of eddy-current losses, especially in silicon-steel, that they form a small part of the total loss, and accurate determinations are extremely difficult. Small errors in observation, or small departures in the wave form, may produce large errors in the value of exponent found.

In the cores of generators and motors, the flux density does not simply alternate in direction, and the relative distribution of flux is not constant. The flux pulsates in space as well as time. The laws of hysteresis and eddy-current loss which obtain with the usual testing apparatus cannot be expected to apply even approximately under such conditions.

TABLE II

B	Temperature in deg. cent.							
	218	237	358	445	527	597	660	707
6000								
8000	1.53	1.60	1.64	1.63	1.77	2.08	1.92	1.99
10000	1.87	1.68	1.68	1.69	1.70	1.54	1.57	1.25
12000	1.81	1.72	1.60	1.61	1.62	1.24	0.85	0.94
14000	1.94	1.72	1.62	1.38	1.31	1.14	1.41	0.60

TABLE III

B	Temperature in deg. cent.					
	47	300	402	508	597	659
8000						
10000	1.79	1.66	1.48	1.04	0.74	0.52
12000	1.68	1.44	1.36	0.96	0.60	1.425
14000	1.54	1.37				

J. D. Ball: In regard to the iron tester for 10 kg. samples 50 cm. by 3 cm., it might be well to add some data as to how satisfactory it has proven in actual practice. Regular checks are made between three laboratories: one located at the steel mill,

one at the transformer factory and one the standardizing laboratory.

The average of 278 samples tested at the mill and factory agree within 1 per cent, the maximum variation of any one sample between the mill and factory measurements was 3.5 per cent. 100 samples tested at a later date show an agreement within 1/20 of one per cent of the same average loss measured in the two places.

Samples tested in all three laboratories show conclusively that average results are well within 1 per cent.

These comparisons are extremely good in as much as the mill test results quoted are results of single observations; the results given at the other points are, in many cases, the average of several observations.

There is one advantage in quoting results as hysteresis loss, as is done when tests are made on the small set (using 1 lb. sample 10 in.x $\frac{1}{2}$ in.) It has been demonstrated that the eddy current loss is a function of the kind, shape and thickness of material and geometrical construction of the test sample or transformer and is independent of total loss or manner of cutting sample as regards direction of rolling.

The hysteresis loss is a value to which may be added the eddy loss to give total core loss at any desired frequency for any size or shape of test sample or transformer after these eddy losses have been determined by separation tests on a comparatively few representative samples.

As is shown in the paper, this is true for the rings and other samples mentioned. It is also shown by Lloyd and Fisher (U. S. Bureau of Standards reprint 109) and other writers. The writer has found it true for various transformer cores of the same types and material.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 25, 1911.

TRANSMISSION APPLIED TO IRRIGATION

BY O. H. ENSIGN AND JAMES M. GAYLORD

The subject of transmission applied to irrigation covers a very broad field of electrical, hydraulic and mechanical engineering. It presents problems of finance and agriculture and must also be viewed from the humanitarian standpoint. There are a number of distinct conditions which lead to the use of transmitted power for pumping in connection with irrigation projects. The more important of these conditions are the following:

1. In some cases high lands which can not be reached by the diversion works constructed for a gravity system can be reached by pumping water from the gravity canals into canals feeding such high land areas.

2. The irrigated area may be advantageously extended by pumping from wells, thus drawing on the underground sources and tending to keep the water plane down, this plan being particularly desirable in certain cases, as will be explained farther on in this article.

3. Pumping may also be applied to the drainage of lowlands, water being pumped to either irrigation or waste ditches.

In connection with the diversion works, it frequently occurs that a considerable amount of hydraulic power can be advantageously developed, and in such cases this power may be transmitted and applied to any or all the purposes named above. Where hydraulic power cannot be developed, steam or other engines must of course be employed.

This paper will be devoted mainly to the discussion of two hydroelectric transmission systems constructed by the Reclamation Service, one applied to the irrigation of high lands by pump-

ing from gravity canals, and the other applied to the extension of the irrigated area by pumping from the underground sources. The former of these has been nearly completed. In the latter, however, only a small portion of the contemplated development has been finished.

It may not be inappropriate in this discussion to call attention to the advantages of pumping the ground waters of an irrigated area. The advantages of such a plan are, first, to prevent the rise of the ground waters to a point dangerously near the surface and, second, to supplement by means of drawing on the underground supplies the water stored in the reservoir or diverted from the natural flow of the streams.

The rise of the ground waters damages the land in an arid climate by allowing evaporation to take place from the surface or from near the surface of the ground, thus increasing the amount of deleterious salts in the surface soil, gradually causing the land to become alkaline in character and non-productive, hence it is essential that the water plane should not rise beyond a certain limit.

It may generally be considered that the thorough watering for irrigation purposes of a large area of land which heretofore has been drained by the rivers which have flowed through it will tend more or less to cause a rise of the ground waters, hence the importance of this particular phase of irrigation.

In some cases the natural underground drainage may be such that the rise of the water plane will be limited to a reasonable depth below the surface, but there are many examples in the West where this has not been the case and lands which were once unusually productive have been made valueless on account of the rise of the water plane. In some instances it may be necessary to drain this water off and let it waste, because it may carry a percentage of salts that would damage the land, but in the majority of cases it may be pumped from wells into canals and distributed.

Southern California presents a good example of this condition, for practically two-thirds of the water supply for this wonderfully productive area is obtained from underground sources. The water plane in a large section of this area is maintained at least 50 ft. (15 m.) below the surface of the ground, thus giving good drainage and constantly improving the condition of the surface soil. All of this pumped water is used for irrigation.

In all irrigation projects, whether by gravity or pumping, the

first thing to be borne in mind is will it pay; that is, can the land stand the charge for the development and the cost of operation of the same. Here the question of climate and the class of products which can be raised upon the soil must be taken into consideration. In some localities a cost of $40 per acre (0.4 hectare) would be a limiting price for the development. In other cases a charge of $100 per acre would not be excessive. The charge for maintenance and operation may vary from $2 to $25 or $30 per acre per annum, the nature of the crop being the controlling feature. It might be mentioned that alfalfa is being grown in Southern California irrigated by water which is pumped from wells, and that orange groves are irrigated by water pumped in some cases as high as 200 feet, both with apparent financial success. On the other hand, to develop water for irrigation in the northern climes, where the season is short, and such crops as alfalfa, grain, potatoes, etc., must be depended upon, the maintenance cost per acre must be kept at a minimum.

Minidoka Project

In the central southern part of Idaho, along the Snake River, The United States Reclamation Service has constructed what is known as the Minidoka project. This project comprises 130,000 acres (52,609 hectares) of land, of which, roughly, 70,000 acres (28,328 hectares) are fed by gravity system on the north side of the river, 10,000 acres (4,046 hectares) by gravity on the south side of the river the remaining 50,000 acres (20,234 hectares) on the south side being supplied with water pumped from the south side gravity canal. (See map, Fig. 1.)

The Minidoka dam, designed primarily to divert water into the gravity canals, was constructed during the years 1904, 1905 and 1906. It is a rock-fill dam with concrete core, located near the foot of the rapids in the Snake River. It creates a fall which averages 46 ft. (14 m.) through the various stages of river discharge, and thus offers an excellent opportunity for development of power. In order that the water might be diverted from the main river channel during the construction of this dam, a deep sluicing channel was made through the lava formation on the north side of the river, and in this sluicing channel was constructed the concrete dam shown in Fig. 2. This structure was built, so far as could then be foreseen, without complete power plant designs, so that it could later be used for the development of power. Through the base of this dam are five sluicing gates,

and higher up are ten 10-ft. (3-m.) circular openings to be used for the power development.

In February, 1908, instructions were given to proceed with the design and construction of a plant at this point to supply power for pumping water to the high-land area 15 miles (24 km.) distant. This work was immediately undertaken and pushed with all possible speed. On the 8th day of May, 1909, one unit in the power plant and one unit in each of the three pumping

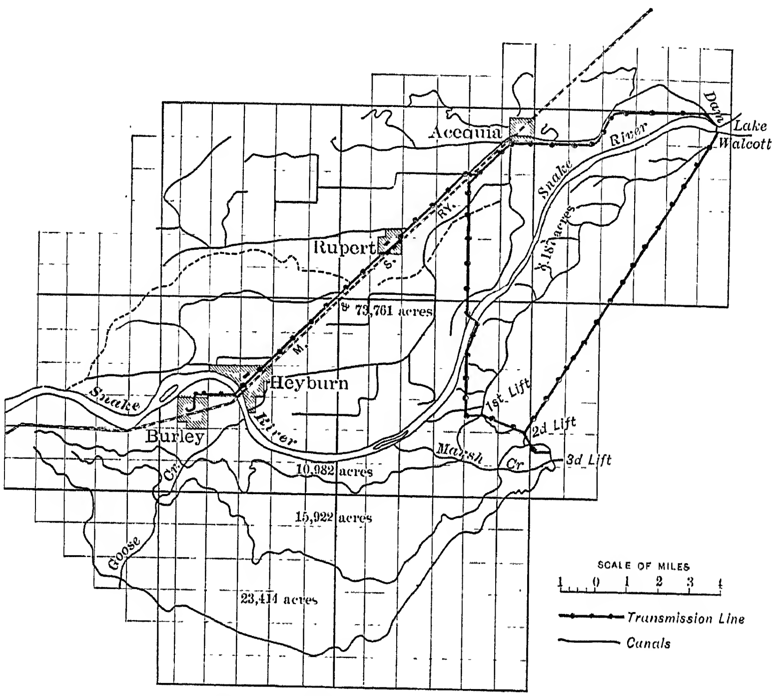


FIG. 1.—Minidoka project, Idaho.

stations were started and operated throughout the irrigation season.

The power plant equipment includes the following:

Five 1400-kilovolt-ampere, three-phase, 60-cycle vertical alternators, each connected to a 2000-h.p. hydraulic turbine.

Two 120-kw., vertical exciter units, each direct connected to a 180-h.p. hydraulic turbine.

Five three-phase, air-blast transformers, delivering 33,000-volt current to the high-tension buses.

The general arrangement of the plant is shown in Fig. 3, and is further illustrated by Figs. 4 to 7.

The turbines are on the lowest floor of the power plant and are carried upon heavy reinforced concrete arches, built up from the bottom of the diversion channel and the buttresses of the dam. The alternators rest upon a reinforced concrete structure and are connected to the turbine shafts by means of clamp couplings. The thrust bearings are located on top of the alternators, which puts the shafts in tension. These are plain collar bearings running in simple oil baths without pressure, and this type of bearing has proven entirely satisfactory. They

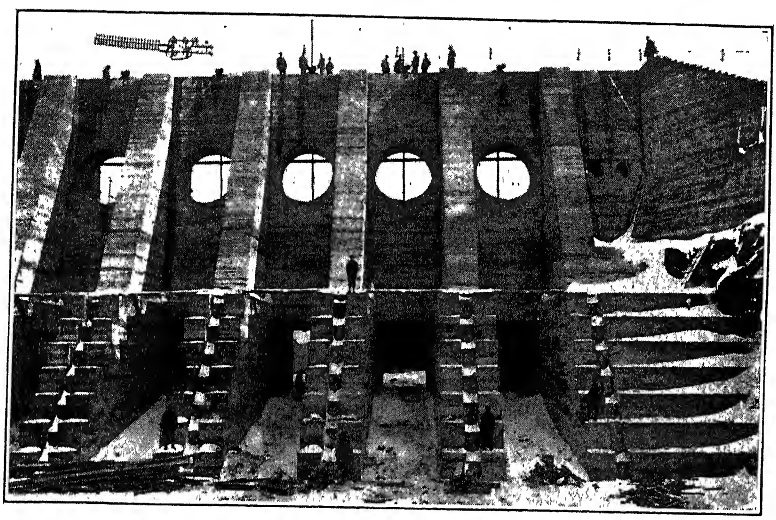


FIG. 2.—Concrete structure in diversion channel, Minidoka dam.

have given no trouble whatever in two years' operation. The arrangement of the exciter units is identical with that of the main generators, except that in the case of the exciters the thrust bearing is located on top of the turbine.

In order to utilize the waste room resulting from the peculiar construction of the dam and the space occupied by the penstocks, a gallery was constructed the entire length of the building along the lower face of the dam and on this gallery are placed the air-blast transformers and high-tension oil switches. The 33,000-volt bus-bars are carried on insulators above this gallery from the south to the north end of the building, where they enter concrete cells and are led to the line switches located at this end

of the building on the generator floor. Below the transformers is a large air duct supplied by two motor-driven fans, and below the air duct on the generator floor all of the governor apparatus is placed. The operating switchboard is at one end of the station and the portion now installed, including the total output panel, faces the machines it controls. It is intended later to extend the present building by adding a wing along the north side of the tailrace, and that portion of the switchboard shown on the drawing for future installation will face this extension. The lightning arresters are located on a special gallery above the switchboard proper.

The hydraulic equipment consists of five $52\frac{1}{2}$-in. (1.33-m.) vertical turbines, arranged in special steel cases which are con-

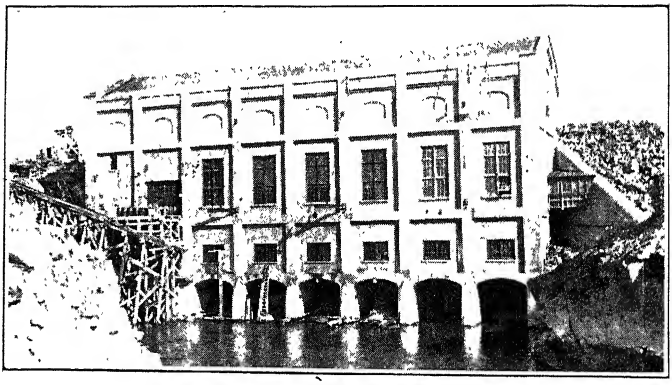


FIG. 4.—Exterior, Minidoka power house.

nected to the dam by means of 10-ft. (3-m.) penstocks, controlled by motor-operated cast iron gates. It was necessary to connect these penstocks and install the gates and trash racks without lowering the water in the lake. The water surface is from 16 to 20 ft. (4.87 to 6.09 m.) above the bottom of these gates, and the problem of installation was solved by designing a special wooden cofferdam, hinged at the top of the dam and which could be swung down against the up-stream face of the structure by filling with gravel pockets provided on the back of the coffer-dam. With the cofferdam in place the space immediately in front of the penstock openings was unwatered by cutting through the stop logs in the 10-ft. (3-m.) opening. By this means the installation of gates and trash racks was successfully and cheaply accomplished.

The governors for the main turbines are all supplied from a central oil-pressure system, consisting of two gear pumps, driven by 40 h.p. direct-current motors, suitable pressure tanks and brass-pipe distributing lines. No receivers or vacuum tanks are used, the oil from the governors being returned to an open tank in order to allow the oil to settle and any entrained gases to escape. Governor heads are provided with means of control from the switchboard, this control being sufficiently close for synchronizing and dividing the load between units, and if need be the turbines can be started and stopped by the switchboard operator.

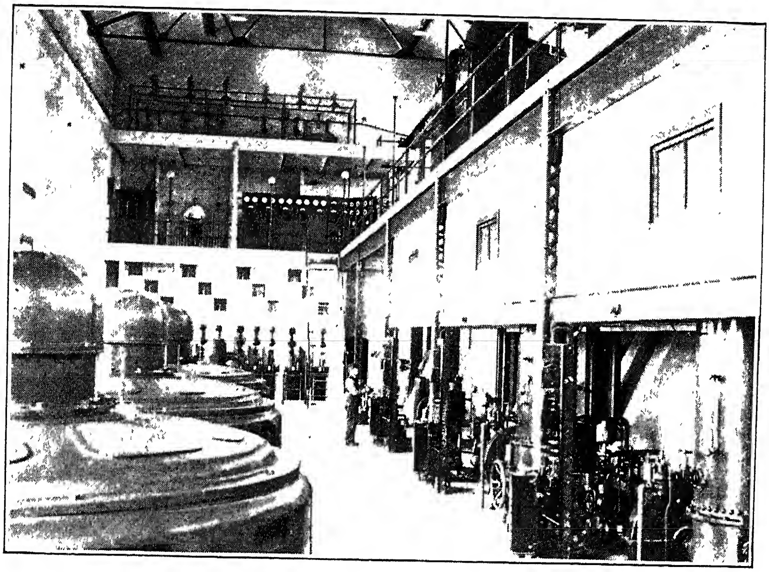


FIG. 5.—Interior, Minidoka power house.

The turbines were designed to meet the following operating conditions: Effective head 46 ft. (14 m.); maximum power 2000 h.p.; speed 200 rev. per min. The maximum efficiency guaranteed by the makers is 81.5 per cent. The guaranteed average efficiency between half and full gate is 77 per cent.

The electrical apparatus is connected on the unit system to duplicate 33,000-volt bus bars. All synchronizing is done at 33,000 volts, oil switches being provided on the high-tension side of the transformers only. These switches are located adjacent to the transformers and are operated by remote control.

Provision has been made for two transmission lines, either of which can be operated from either bus.

The operating characteristics of the power plant apparatus are as follows:

Alternator, 1400 kilovolt-amperes, 2300 volts, three phase, 60 cycles, 200 rev. per min.; regulation at 100 per cent power factor, 8 per cent; efficiency at full load, 96 per cent; temperature rise at full load, 40 deg.

Transformers, 1400 kilovolt-amperes, low voltage 2300, high voltage 33,000 *Y*. Regulation at 100 per cent power factor, 0.9 per cent; temperature rise at full load, 40 deg.; efficiency at full load, 98.4 per cent.

All of the apparatus has exceeded the requirements of the specifications in actual performance.

FIG. 6.—Tail race excavation, Minidoka power house.

The transmission line, consisting of a single circuit of No. 3 and No. 5 B. & S. copper, carried on wooden poles, is 22 miles (35.4 km.) in length and crosses the Snake River in an 1150-ft. (350-m.) span of six-strand, 83,000-cir. mil copper cable at a point 11 miles (3.3 m.) below the power plant. A second similar line is being constructed on the south side of the river, using No. 5 wire, and the two lines will be connected as a loop system through the stations and to the towns on the project which are being supplied with light and power.

There are three pumping stations, each having a lift of 31 ft. (9.4 m.). No. 1 contains 5 pumps, four of 125 second-feet capacity and one of 75 second-feet capacity; No. 2 four pumps, each of 125 second-feet capacity; and No. 3 three pumps, two

of 125 second-feet and one of 75 second-feet capacity. The general arrangement of these pumping stations is shown in Fig. 8.

The problem in a system of this kind is to supply at as high an efficiency as practicable, taking into consideration operating conditions, first cost and maintenance, water in variable quantities with the least liability of shut-down and the least possible operating expense. Bearing this in mind, the choice of design of pumping station and especially the arrangement of the pumping units requires no small amount of study. The ordinary

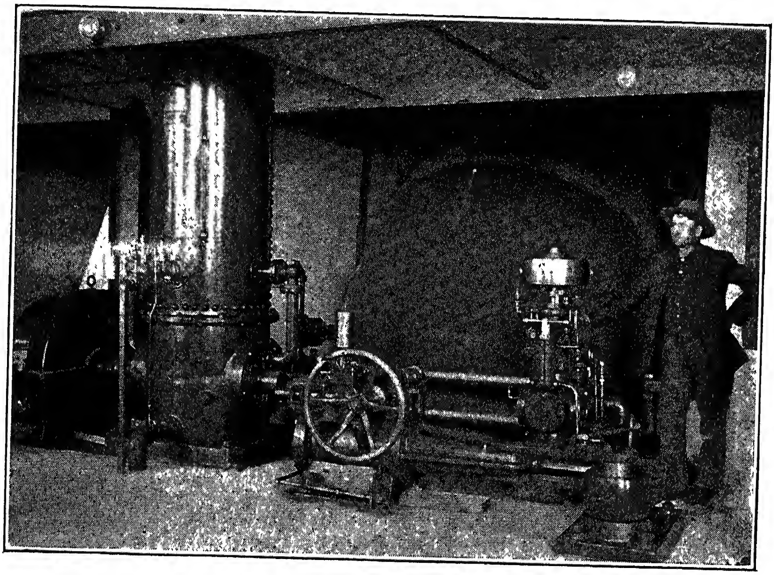


Fig. 7.—Oil pump and governor, Minidoka power house.

horizontal pump with the necessary foot valves would have made an expensive and awkward plant, and such an arrangement would have required a much larger amount of floor space than that occupied by the vertical units which were finally decided upon. The foot valves alone would have introduced a serious loss of head by offering considerable friction, and the control of the discharge of the water by means of gate valves would have involved an expensive installation and a constant source of annoyance in operation. The idea of controlling this pump by means of a cylinder gate, similar to those used in water turbines, resulting from a careful study of the problem, was carried out

with very satisfactory results. By means of this gate the flow of water in the canals is under close control by the operator in the pumping station.

The pumps are installed in separate compartments and are

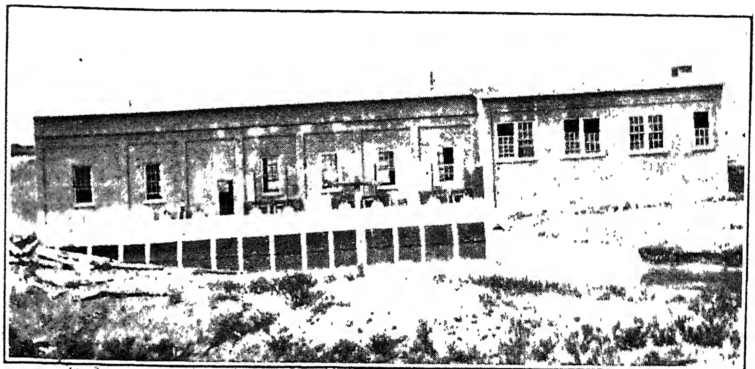


FIG. 9.—Pumping station No. 1, Minidoka project.

direct connected to synchronous motors located directly above them and supported by a heavily reinforced concrete structure. As in the case of the generators at the power house, the weight of the rotating element is carried by thrust bearings located

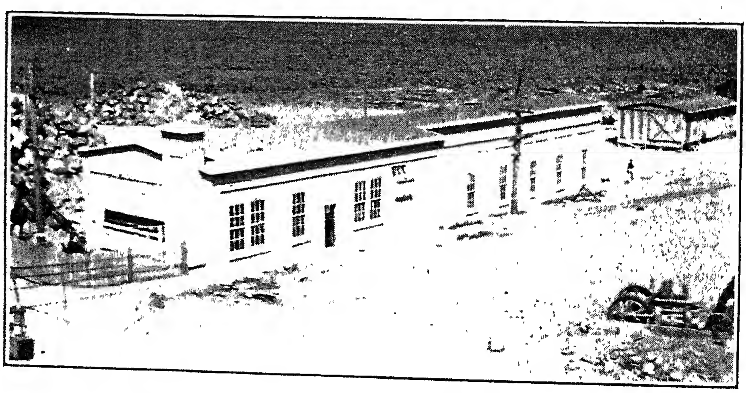


FIG. 10.—Pumping station No. 2, Minidoka project.

on top of the motors. In this case, however, the bearing is of the roller type, this style of bearing having been adopted on account of the necessity of reducing friction to a minimum in starting the synchronous motors.

Motor-operated steel plate sliding gates are used to admit water from the forebay to the pump pits, two gates being provided for each pit. Provision has been made for pumping out the pits in order that the synchronous motors may be started without load other than friction and windage of the rotating parts. For this purpose an auxiliary six-inch (15.24-cm.) centrifugal pump was provided and arranged so that its suction could be

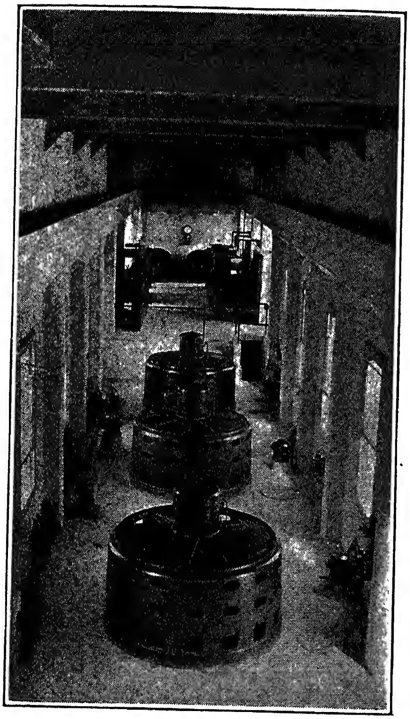


FIG. 11.—Interior pumping station No. 1, Minidoka project

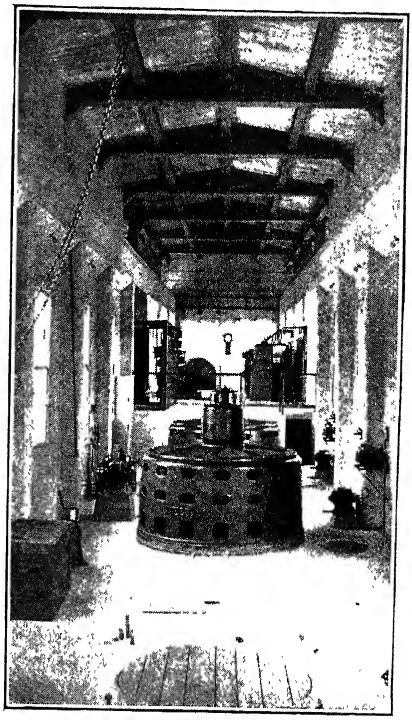


FIG. 12.—Interior Pumping station No. 2 Minidoka project

connected to any pit and the water entirely removed before the motor is started.

When the plant was first designed, it was thought inadvisable to adopt an arrangement by which the pumping units could be started in quick succession, on account of the danger of the sudden rush of water down the canal injuring the banks. The auxiliary pump, therefore, is of only sufficient capacity to permit starting of pumps at intervals of 20 to 30 minutes. Two years'

operation has shown this to be an unnecessary precaution, and by means of a specially designed starting valve each pump is now arranged so that it can empty its own pit while the motor is running on the compensator in starting. As soon as the pit is emptied the motor approaches synchronous speed and the field is excited. This arrangement has worked out very satisfactorily, and by its use a pump can be started up and put into full operation inside of two minutes.

Each pump has but one guide bearing, a long sleeve with a stuffing box at the top, and near the top of the sleeve the bearing is supplied with a semi-hard oil having the consistency of vaseline, forced in by a special motor-driven pump for each individual bearing. Lubricating in this manner forces the lubricant downward and excludes water from the bearing and any possible grit which may be in the water. In two years' time no rust or wear is shown on these bearings, the shaft being as bright as when it came from the factory.

Curves giving the characteristics of the pump as to efficiency, power and gate openings are shown in Fig. 13.

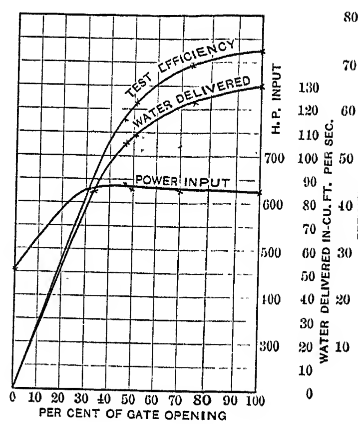


FIG. 13.—Test of 125-ft.-per-sec. centrifugal pump

The upper end of the $5\frac{1}{2}$-ft. (1.67-m.) concrete force mains leading from the pumps is closed by a check valve, to prevent water from running back to the pump in case of a shut-down. This valve is made up of $\frac{1}{4}$-in. (6.35 mm.) boiler plate slightly bumped, hinged from the top of the head wall and seating against rubber packing set in a cast iron ring.

The 600-h.p. motors for driving the 125-second-foot pumps are of the self-starting synchronous type, operating at 300 rev. per min. and receiving 60-cycle, three-phase current at 2200 volts.

When operating as generators the characteristics are as follows:

Efficiency at full load, 100 per cent power factor, 94 per cent;
Regulation at 100 per cent power factor, 8 per cent;
Temperature rise at full load, 40 deg.

The motors for operating the smaller pumps are similar except that they have a capacity of 360 h.p. and the following operating characteristics;

Efficiency at full load, 100 per cent power factor, 94 per cent;
Regulation at 100 per cent power factor, 8 per cent;
Temperature rise at full load, 40 deg.

The rotors are provided with squirrel-cage windings, to permit starting as induction motors, receiving for this purpose current at low voltage from compensators. The compensator voltage is so adjusted that the starting current drawn from the line does not exceed normal full load operating current of the motor, and

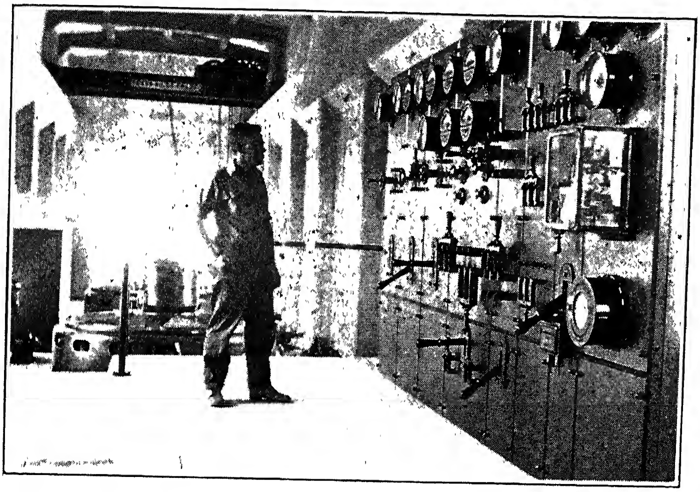


Fig. 14.—Switchboard pumping station No. 2, Minidoka project.

by careful manipulation the motor can be brought into step with the line without exceeding this. It has been found that this can be most easily accomplished by exciting the fields while the motor is running at low voltage on the compensator and then throwing over to full voltage with the machine running steadily at synchronous speed.

The step-down transformers are of the three-phase, air-blast type, receiving 30,000-volt current through oil circuit breakers from the high-tension bus and delivering the 2,200-volt current through disconnecting switches and expulsion fuses to the low-tension bus.

The transformer characteristics are as follows:

Efficiency at full load, 100 per cent power factor, 98 per cent;
Regulation at 100 per cent power factor, 1.1 per cent;
Temperature rise at full load, 40 deg.

In pumping station No. 2 are installed the transformers necessary for station No. 3. The distance between stations 1 and 2 is $1\frac{1}{2}$ miles (2.4 km.), and between stations 2 and 3 three-quarters of a mile (1.2 km.), the highest voltage carried to the latter station being 2,200.

The exciters and blowers for the transformers are driven by induction motors and a motor-driven air compressor has been provided for cleansing the apparatus in each station. Lightning protection is provided in the form of electrolytic arresters placed inside the building.

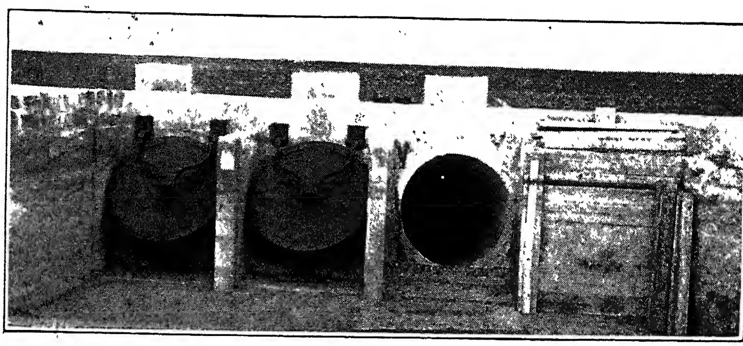


FIG. 15.—Check valves at head of discharge pipes. Pumping station No. 2, Minidoka project.

All the switching apparatus in the pumping stations is operated by distant mechanical control. A single high-tension bus has been provided, but provision has been made by means of disconnecting switches for receiving power from either or both transmission lines.

The power house and substation buildings up to the motor and generator floor were built during the winter between the middle of November, 1908 and the first of February, 1909, and during this time the weather was very cold, reaching to as low as 15 deg. below zero. Considerable rock excavation was necessary at pumping station No. 2, and at the tail race for the power plant, and the concrete work on all of the structures had to be protected from freezing until set by means of artificial heat.

The apparatus, consisting of one unit in each station, was started in the spring of 1909 in temporary wooden structures covering the motor and generator floors; around these structures

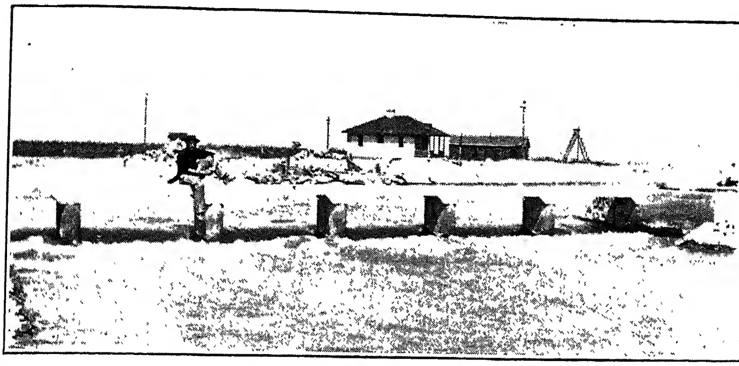


FIG. 16.—Canal above pumping station No. 1, showing pumped water, Minidoka project.

permanent buildings were finished during the summer. During the winter of 1909–1910 additional units were installed for the operating season. At the present time two additional units

FIG. 17.—Pumping station No. 3, Minidoka project.

are being installed in the generating stations and two pumps in the pumping stations and during the winter of 1911-1912 three more pumps will be installed.

The following table of costs, when considered in connection with the strenuous conditions under which these plants were constructed, may be of interest. The figures given in the table do not include the cost of operators' quarters and road making. These items have been omitted, since they are so greatly dependent upon local conditions. The erection costs, however, include several items such as the cost of making preliminary tests of the hydraulic apparatus, the cost of temporary buildings for housing machinery during the time the permanent buildings were under construction and other items made necessary by the severe conditions under which the plants were constructed.

TABLE I

CONSTRUCTION COST OF MINIDOKA POWER AND PUMPING SYSTEM

	Power plant	Pumping station No. 1	Pumping station No. 2	Pumping station No. 3	Trans-mission line	Total
Capacity	6,500 kw.	2,500 kw.	3,000 kw.	1,300 kw.	6,500 kw.	6,500 kw.
Building	$80,200	$34,500	$40,300	$19,200	—	$174,200
Machinery	167,600	78,800	73,600	32,500	—	352,500
Freight and hauling	25,100	11,800	10,600	6,100	—	53,600
Erection	62,300	18,200	16,800	8,600	—	105,900
Engineering and incidentals	13,600	5,600	5,300	2,800	—	27,300
Tail race	56,600	—	—	—	—	56,600
Pressure pipes	—	19,000	14,000	16,600	—	49,600
Double transmission line	—	—	—	—	35,000	35,000
Total	$405,400	$167,900	$160,600	$85,800	$35,000	$854,700
Unit cost	$63.00	$67.00	$53.00	$66.00	$5.40	$132.00

A large portion of the riveting of the turbine cases, penstocks and draft tubes was done in the field. In fact, the penstocks and draft tubes were completely assembled at the plant.

It may also be noted that the cost per kilowatt of station No. 2 is based on its transformer capacity of 3,000 kilowatts, while the unit cost at station No. 3 is based on its motor capacity.

In table II is shown the estimated operating cost, based on the actual cost of operation during the season of 1910, of that portion of the equipment then installed. There are two operators on each shift at the power house and there will be but one operator on each shift at each of the pumping stations. The

cost of repairs during the season of 1910 was so ridiculously low that the figures given in the table are greatly in excess of the actual cost of repairs last year. This also applies to superintendence and general expense. Five per cent per annum depreciation has been allowed on the power installations, including buildings, and 10 per cent per annum on the transmission lines. No interest charge appears, since funds for the construction of

TABLE II

ESTIMATED MONTHLY OPERATING COSTS OF MINIDOKA PUMPING SYSTEM BASED ON ACTUAL COST DURING SEASON OF 1910 EXCLUSIVE OF DITCH TENDING

	Power plant	Pumping station No. 1	Pumping station No. 2	Pumping station No. 3	Transmission line	Total
Capacity	6,500 kw.	575 sec. ft.	500 sec. ft.	325 sec. ft.	6,500 kw.	—
Labor	$700	$300	$300	$300	$100	$1,700
Supplies	150	30	30	15	5	230
Repairs	75	20	20	10	10	135
Superintendence and general expense	400	200	200	150	40	990
Depreciation	1,460	670	670	350	300	3,450
Total	$2,785	$1,220	$1,220	$825	$455	$6,505
Acre feet pumped	—	25,000	20,000	15,000	—	—
Acre feet pumped 1 ft. high	—	750,000	600,000	450,000	—	1,800,000
Kw-hr	3,600,000	1,500,000	1,200,000	900,000	—	3,600,000
Cost per acre ft. 1 ft. high	0.154 ct.	0.163 ct.	0.203 ct.	0.183 ct.	—	0.362 ct.
Cost per kw-hr	0.077 ct.	—	—	—	—	0.18 ct.
Cost per acre per season	—	—	—	—	—	78 ct.

Depreciation at 5 per cent per annum on complete power installation, 10 per cent on line.
Estimates for the six months of the irrigating season assuming that the winter operating expenses are covered by the sale of power.
Allows three acre-feet per acre during season over 50,000 acres.
Average lift 73 feet.

all reclamation projects are, in reality, loaned by the United States to the settlers without interest.

The figures giving the acre-feet pumped by each station were arrived at by comparison of the installed capacity and the acre-feet pumped during the season of 1910, with the ultimate capacity of the various pumping stations and it is found that the figures thus obtained check very closely with the amount of water estimated to be necessary for the successful raising of

crops on these lands; namely, three acre-feet per acre per season. The acre-feet pumped one foot high was found for each station by multiplying the total acre-feet for that station by the approximate net lift, namely, 30 ft. The results of last season's run showed that the kilowatt-hours generated at the power plant were almost exactly double the acre-feet pumped one foot high by the pumping stations; and since one kilowatt-hour is equal to 1.01 acre-feet one foot high, this would indicate a working efficiency from power plant to water delivered in the upper canals of approximately 50 per cent. This actual working efficiency should be compared with the following table of full load efficiencies, starting with the water behind the dam and working through the system to the water delivered in the upper canals. The cost of operation per acre-foot pumped one foot

TABLE III
FULL LOAD EFFICIENCIES

	Efficiency	Net efficiency from water behind the dam
Turbines	81.5 per cent	81.5 per cent
Generators	96.0 "	78.2 "
Step-up transformers	98.4 "	77.0 "
Transmission line	90.0 "	69.3 "
Step-down transformer	98.0 "	67.9 "
Motors	94.0 "	63.8 "
Pumps	72.5 "	46.3 "

high given for the various pumping stations might be taken to represent what a company would expect to pay for operating expenses, exclusive of the cost of power in a pumping station of this character.

In the table of operating cost it has been estimated that the entire winter operating expenses, including fixed charges, will be covered by the sale of power and that the land under the pumping system will not be charged with any standby expenses for the winter season. In such a system as this, where a large amount of power is required during the summer irrigating season, and none during the winter season, the development of a winter load is very desirable, and with this in view, the transmission lines have been extended to the towns of the Minidoka Project and power is there sold for commercial purposes. Extremely low rates

are offered for electric heating and the use of large amounts of power for all purposes during the winter is encouraged in every possible way. By furnishing power at very low rates, especially during the winter months, the annual operating and maintenance charges against the pumping system are reduced and the settlers on the project, who have paid for this work, have the benefit of cheap light, power and electric heat.

SALT RIVER PROJECT

Transmission applied to irrigation on the Salt River Project is an entirely different problem from that on the Minidoka Project. On the Minidoka Project the only method by which

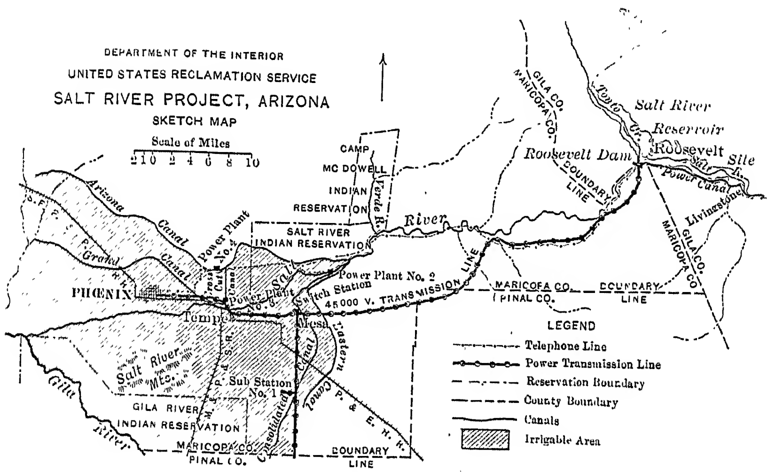


FIG. 18.—Map of Salt River project.

water could be obtained for 50,000 acres of land was through the medium of the pumping system. On the Salt River Project a storage reservoir, diversion works and canals are constructed, prepared to irrigate about 260,000 acres (105,218 hectares) of land by gravity and pumps. The pumping system will serve two purposes; one is to prevent the rise of the ground waters to a point dangerously near the surface, and the other is to supplement by the means of drawing on the underground supply, the water stored in the reservoir and delivered by the natural flow of the streams.

The power development at the Roosevelt dam consists of two separate hydraulic developments, one from a power canal con-

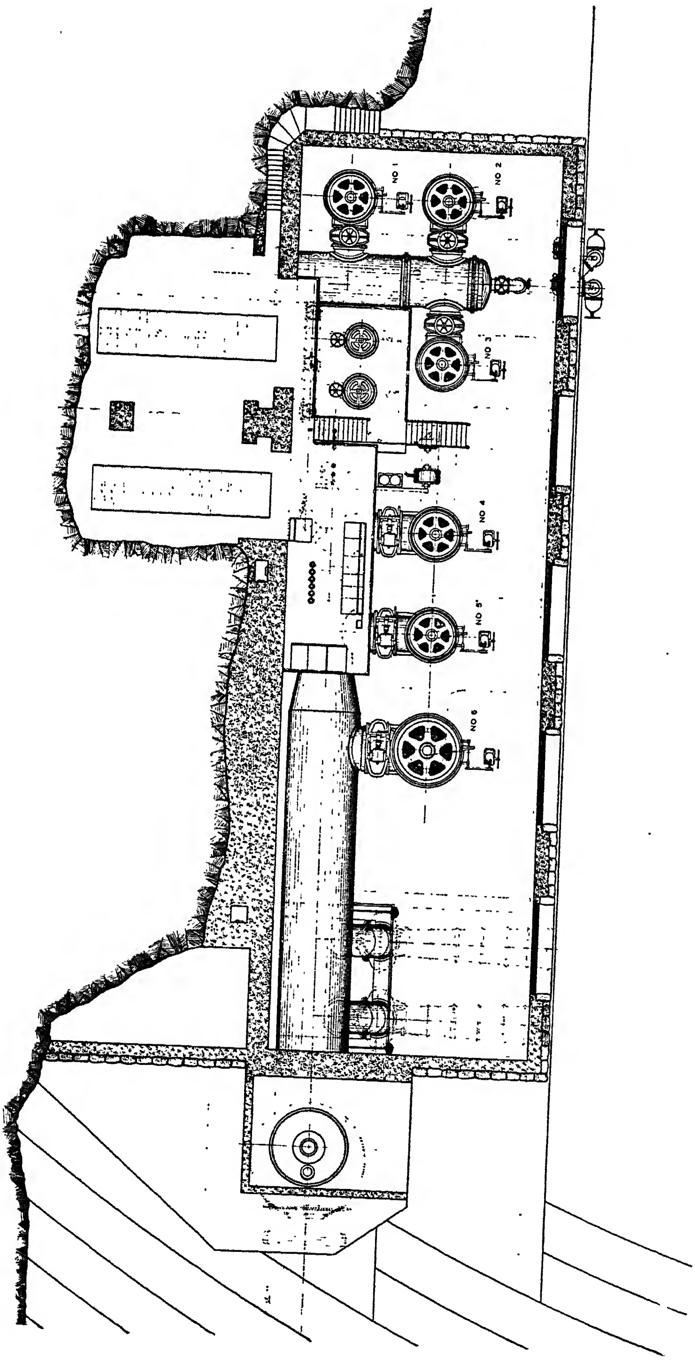


FIG. 19.—General plan of power house, Salt River project

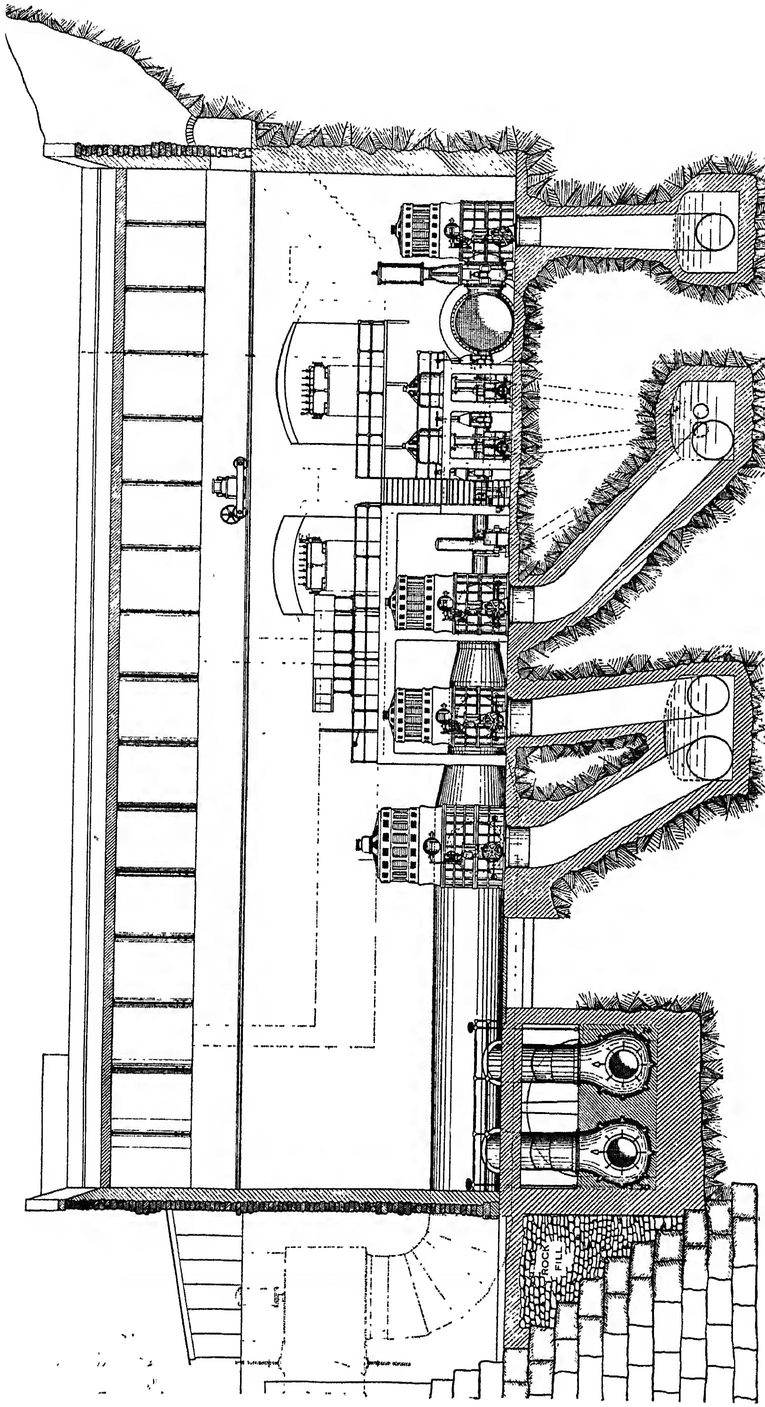


FIG. 20.—Section of power house, Salt River project.

structed to furnish power for building the dam, and ultimately for permanent power purposes; the other using the water from the reservoir as it is discharged for irrigation purposes. The first installation at the reservoir consisted of a turbine and generator in a cave excavated in the face of the cliff, a short distance below the toe of the dam. This cave is now used as a compartment for low-tension switch installation. In the early stages of the work this form of development was necessary on account of the heavy blasting in the vicinity and the consequent danger of damage to apparatus less securely housed. Early in the construction work, however, plans were developed for a complete power plant, shown

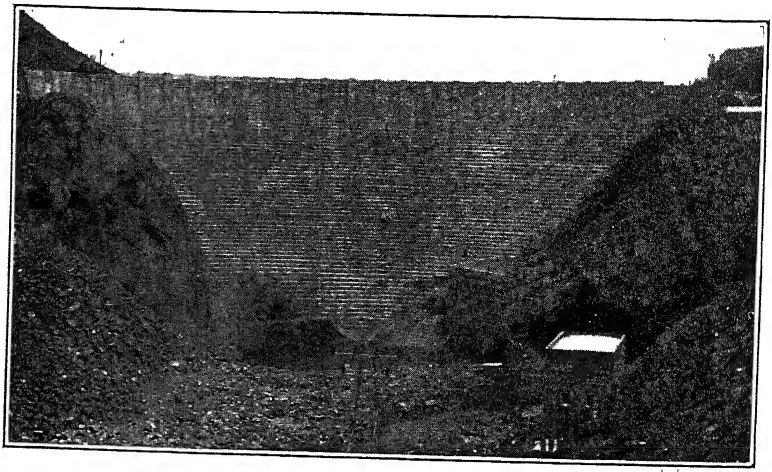


FIG. 21.—Roosevelt dam showing power house and transformer house in foreground.

in Figs. 19 and 20. The power plant was constructed upon a rock foundation formed by excavation of the canyon side. The draft tubes and tail race tunnels are constructed in solid rock. The water from the power canal is brought to three of the units through an incline tunnel, lined half way down with concrete only, the balance of the way the concrete is lined on the inside with $\frac{5}{16}$-in. (7.9-mm.) steel plate. Extending from the lower end of the tunnel the seven-foot (2.1-m.) penstock is made up of $\frac{5}{8}$-in. (15.8-mm.) butt and strap riveted steel plate and is connected to three units capable of being operated continuously at 1200 kw. The static head is 226 ft. (68.8 m.) On account of the heavy rock excavation necessary to get sufficient room for

the building, economy of space was an important consideration in the design of the plant. This led to the selection of the vertical type of generating unit shown in the illustrations.

The other development is a 10-ft. (3-m.) penstock through the dam, controlled with a large cylinder gate just outside the power house. To this penstock will be connected three units, one of

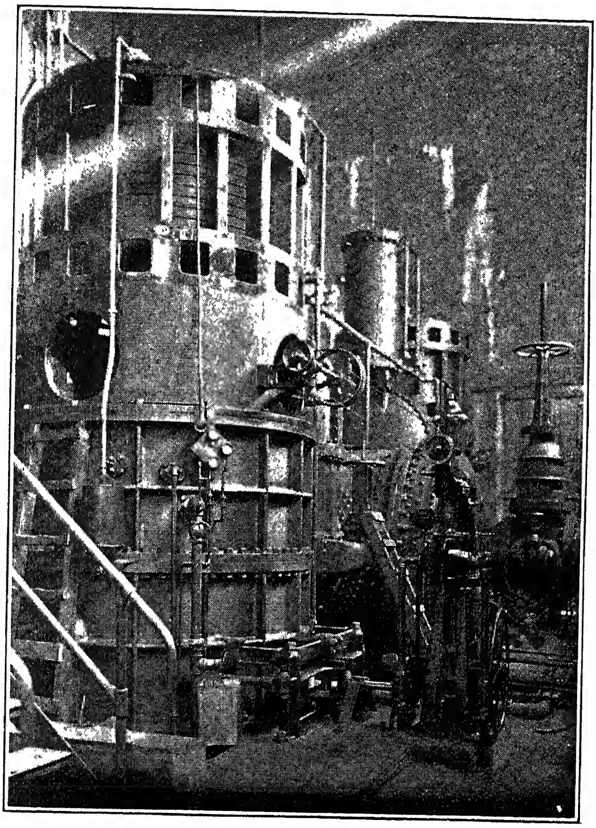


FIG. 22.—Interior, Roosevelt power house, before completion, showing vertical turbines and generators.

them of 2000-kw. and the other of 1200-kw. capacity. The operating head for which these turbines are designed to give the maximum efficiency is 160 ft. (48.7 m.), and it is expected that they will be controlled to operate at heads ranging from 90 to 220 ft. (27.4 to 67 m.). The reservoir contains above the 110-ft. (33.5-m.) level, 90 per cent of its full capacity. It may, there-

fore, be seen that when the reservoir gets below 160 ft. (48.7 m.) while the power of the wheels will fall off greatly, the total amount of energy that is available in the reservoir is not very great.

The generating units operate at 500 rev. per min., producing three-phase, 25-cycle, 2300-volt current. The operating characteristics of these generators are:

Efficiency at full load and 100 per cent power factor, 95 per cent;
Regulation at 100 per cent power factor, 5 per cent;
Temperature rise at full load, 35 deg.

There is a double bus bar switchboard with selector switches for both transformers and generators. These switches are located in the power house and are controlled by a benchboard. The transformers and high-tension switches are located in a separate building, about 600 ft. (182.8 m.) from the power plant. The transformers rest on large castors and are in fire-proof compartments, each three-phase group being isolated by concrete barrier walls. Switches and bus bars are all enclosed in concrete cells. The transformers have a nominal capacity of 350 kilovolt-amperes, but have shown such good regulation and low heating characteristics that they may be operated continuously at nearly double this capacity without exceeding the temperature limits of the Standardization Rules. There are six groups of these transformers, transforming from 2,300 volts delta to 45,000 volts Y, the voltage of the transmission line.

The transmission line consists of six 83,000 circular-mil, six-wire, hard drawn copper strands, supported on 14-in. (35.5-cm.) insulators having a flash-over test of 165,000 volts dry. The line is supported on steel towers with the lowest wire at an average elevation of 30 ft. (9.1 m.) from the ground in the mountains, and a limiting distance of 30 ft. (9.1 m.) from the lowest wire to the ground in the valley. The towers average a distance of 360 ft. (109.7 m.) apart in the mountains, on account of rough country, and 400 ft. (121.9 m.) apart in the valley. This line is 65 miles (104.6 km.) long, reaching to Phoenix, Ariz., the largest town on the project. A branch line taps off from a four-way switching station 40 miles (64.3 km.) from the power house, near the town of Mesa and runs south 20 miles (32.1 km.) terminating in a substation at the Pima Indian Reservation. There is also, about 10 miles (16 km.) south of the main line, another substation for general irrigation pumping. It is contemplated that in the future practically all the power

of this plant will be used for irrigation purposes, although at the present time it is supplying the local distributing company in the city of Phoenix with power under a modification of an old contract, in effect before the Reclamation Service commenced work. After the line reaches the cultivated district, the tripartite form of steel pole is used instead of steel towers, on account of the ground space that was saved by such use. Thirty miles (48.2 km.) of this line was exceedingly difficult to construct. In some places the wire had to be drawn through by cables for

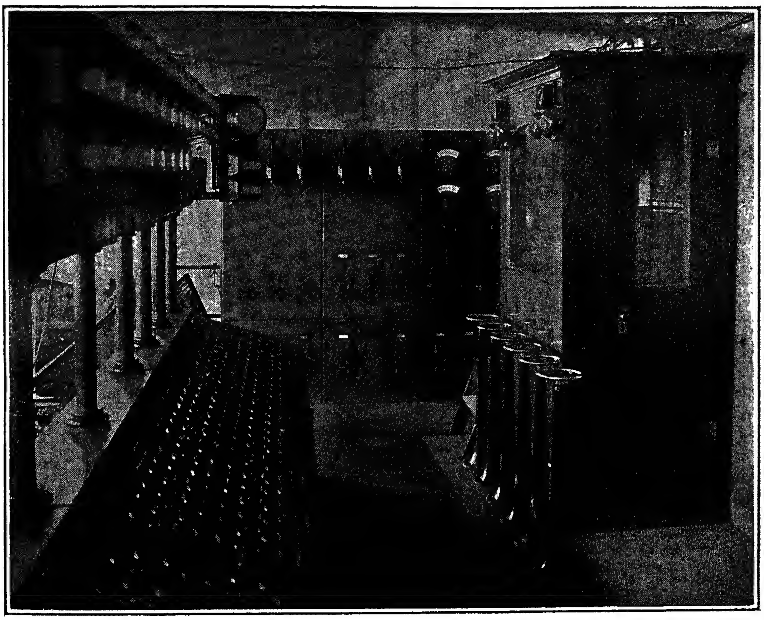


FIG. 23.—Switchboard, Roosevelt power house.

nearly three miles (4.8 km.), as it was inaccessible by the road. The line was constructed by pulling the wire under tension by means of a steel hauling line over sheaves placed on the cross arm. The cost of 65 miles (104.6 km.) of two-circuit line was $4,400 per mile (1.6 km.).

The main transmission line of this system has given absolutely no trouble since the day it was started from any cause that can be traced to the line itself, that is, failure of insulators, towers or similar causes. Shortly after the line was put into operation, however, it developed that large hawks, which exist

in great numbers in the plain adjacent to the cultivated area, covering about 18 miles (28.9 km.) of the main line, caused frequent interruptions by alighting on the towers and short circuiting the wires with their wings. The local superintendent has overcome this by installing on the cross arm a small casting provided with sockets, in which are rods of hard wood projecting upwardly, forming sharp points between the insulators. These are very effective and entirely stopped the trouble. The large birds are extremely careful about injuring their wings or themselves in lighting near any such device. The same thing occurred on the branch line recently constructed and this remedy was applied.

The wires are arranged on the towers forming equilateral triangles with 48-in. (1.2-m.) sides.

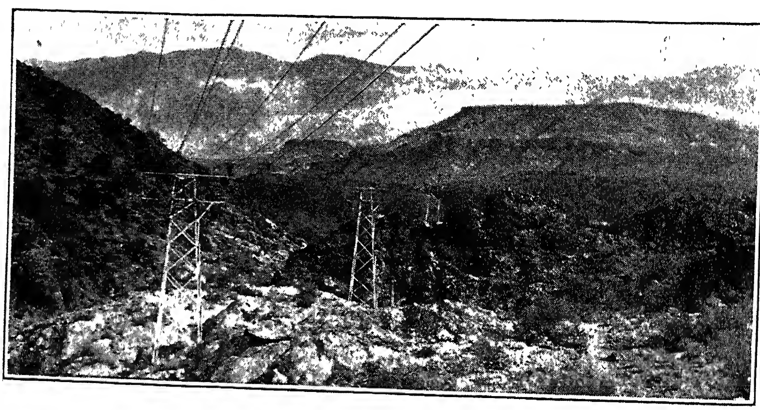


FIG. 24.—Roosevelt-Phoenix transmission line through the mountains.

One section of the irrigation development by pumping is about completed. This is 12,000 acres (4,856 hectares) of land, to be supplied almost wholly by pumped water, on the Pima Indian Reservation at Sacaton, near the Gila River. There is a flood ditch which will supply water from the Gila when it may be in flood. This is a very erratic stream and can not be depended upon, but its waters are useful in supplying fertilizing qualities to the soil, since it carries a vast amount of silt and dissolved valuable fertilizing material. In the main, however, these 12,000 acres (4,856 hectares) of land will depend upon the pumps. A line of wells was located, about two miles (3.2 km.) from the Gila River, slightly diverging towards the north from the river,

These wells consist of first, a 16-in. (0.4 m.) California well casing driven to a depth of 200 ft. (60.9 m.); a large portion of this depth was found to be of coarse gravel. Around this was sunk a concrete caisson, nine ft. (2.7 m.) in diameter, to a depth of 55 to 60 ft. (16.7 to 18.2 m.). In sinking these caissons a pump having a capacity of 12 second-feet was used, and when a depth was reached which corresponded to the capacity of that pump, to keep the pit dry for excavating purposes, the work was

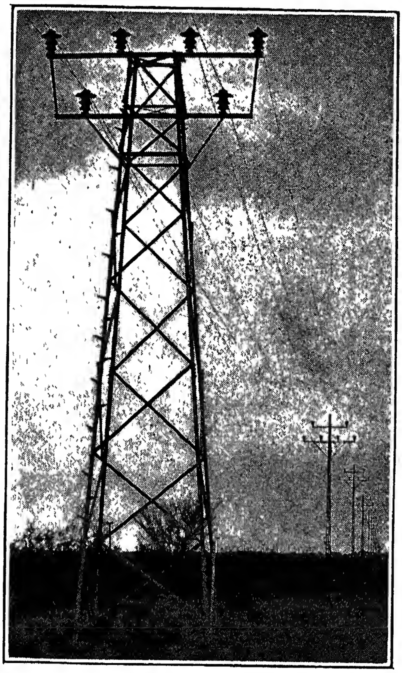


FIG. 25.—Roosevelt-Phoenix transmission line in the valley.

stopped. The top of the caisson was then finished into a small square building for the installation of apparatus. Motor, transformer, pump, etc., were installed as shown in Fig. 26.

The specifications for this pump required a maximum efficiency at five second-feet and 55 ft. (16.7 m.) lift, of 70 per cent, and at 35 ft. (10.6 m.) lift and a correspondingly increased capacity, an efficiency of 63 per cent. In the effort to meet these conditions on a flat top efficiency curve so the motor would not be overloaded at lower heads, the manufacturer obtained a

pump giving exceedingly fine results, namely, 80.6 per cent, including the suction elbow and discharge elbow, at 5.5 second-feet and 55 ft. (16.7 m.) lift. The efficiency curves of this pump are shown in Fig. 27.

The pump is a top-suction, vertical shaft pump, carried between galvanized steel channel, forming a frame, which carries a suitable number of cast iron supports and guide bearings. The guide bearings have a pan case on the top to receive hard oil. At the top of the pump shaft is an oil-lubricated thrust bearing in action only as the pump is started. As soon as a small head of water is produced by the pump, a portion of the area of the bottom of the impeller becomes a thrust bearing, which as it starts to lift the impeller, uncovers openings from this thrust area in to the center of the volute, and the opening of these passages balances the pump and stops the impeller in proper

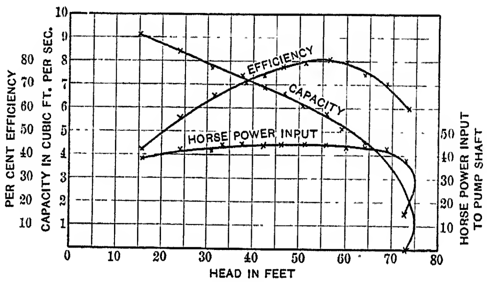


FIG. 27.—Test of 10-in. centrifugal pump, Salt River project.

alignment with the volute, thus carrying the weight of the impeller and shaft always on a water thrust.

This water thrust is adjustable by means of a plug attached to a lever and rod leading up to the motor base. A cast iron base for the motor is fastened to the top of the frame by bolts. The top of the vertical shaft is fitted with a jaw coupling. The motor is placed on the cast iron base with the other half of the coupling on the motor matching into the one on the pump shaft and is bolted in this position. The jaw coupling allows vertical movement of the pump shaft as above described. The motor itself has an independent oil-lubricated thrust bearing. Ball bearings are not sufficiently reliable for an installation of this kind, for the breakage of a ball, with the attendant ten miles (16 km.) away, would have serious consequences. Some form of bath bearings is best adapted to this work. In this case the

bearing consists of large cast iron collars furnished with a slight oil pressure from a small gear pump located in an oil reservoir holding several gallons of oil and placed at the top of the motor.

The whole mechanism of motor, pump and frame rests on *I*-beams, grouted in the concrete of the caisson. The motor can be unbolted and lifted out and the frame and pump then lifted out independently for examination. The discharge pipe is composed of galvanized riveted iron pipe hung in the caisson in the same way as the motor and frame. The remainder of the electrical equipment consists of 10,000-volt oil switches, a 10,000 to 220-volt, three-phase, self-cooled transformer, pro-

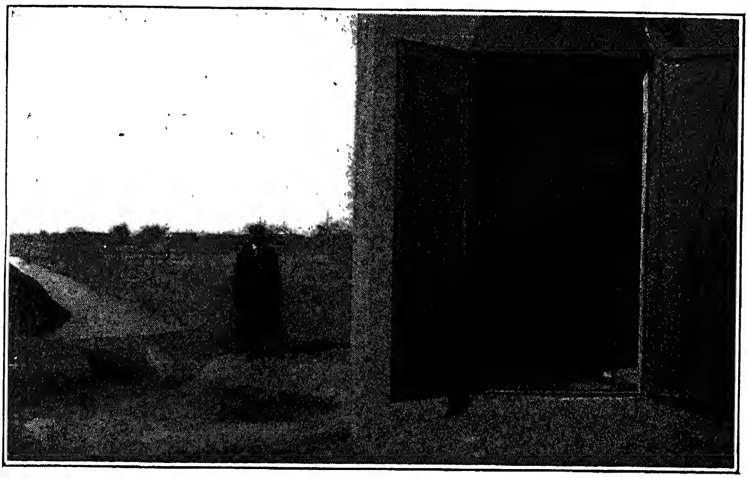


FIG. 28.—One of the Sacaton wells, Salt River project.

vided with taps for starting the motor at half voltage; a double-throw, triple-pole knife switch and an ammeter.

Ten of these units in a line ten miles (16 km.) long, and a 750-kilowatt substation, with provision for extension to 1500 kilowatts, are taken care of by two men, one of them an Indian. The pumps run with very little attention. Similar motors on another installation have operated for two years without giving any trouble whatsoever. Similar installations of pumps the writer has known to operate for long periods, with very little attention.

This pump running submerged is always working at its best efficiency. By using a large pump to sink the caisson all the

fine material is drawn out of the gravel in the vicinity of the bottom of the caisson and no more sand will be drawn into the well at the reduced capacity of the permanent pump.

Operation to date has given an average minimum discharge of six second-feet for each well, which corresponds to a lift of approximately 50 ft. (15.2 m.) and a pump efficiency of approximately 80 per cent, as will be seen by reference to the test curves of the pump.

The whole pumping system is an exceedingly reliable one. Practically the only attention which seems to have been found necessary to date is the restarting of the pumps after an interruption. It is proposed that this may be finally solved for each group of this kind by starting them all from the substations by means of a compensator in the substation itself con-

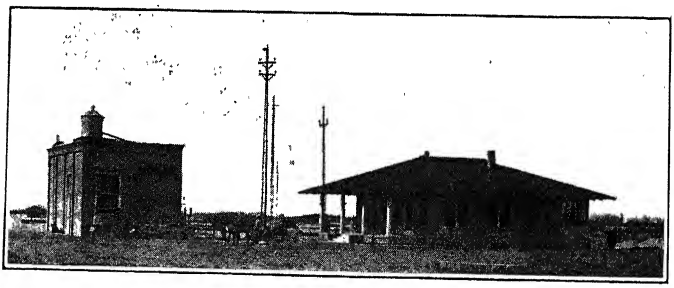


FIG. 29.—Substation, pumping plant and operators house.

nected in the 10,000-volt circuit distributing to these pumping plants.

Taking this plant as it stands, solely as a pumping development, without the flood canal, in which case the area supplied would be limited to 10,000 acres (4,046 hectares) instead of 12,000 acres (4,856 hectares) we find some interesting results, as to cost, and it is believed that these results can be improved upon in the next installation of this character, by taking advantage of the experience gained in the sinking of caissons in this installation and probably a saving of 15 to 20 per cent might be made on that portion of the work. The cost of the ten wells and pumping equipment is $105,000, or about $10 an acre (0.4 hectare) for the 10,000 acres (4,046 hectares) which they will supply. Assuming that a power company stands ready to supply the current to the 10,000-volt line in regular commercial

work, the following interesting results of cost of irrigation by this method may be deduced.

As shown by the efficiency curve of the pump, the horsepower input to the pump at any head which will probably be maintained in these wells will not exceed 44 h.p. Taking into account shaft losses, piping losses and loss in efficiency of the pump as time goes on, it may be assumed that 50 h.p. applied to the pump is a reasonable figure. The load on the substation calculated from the proven efficiency of apparatus and line would be then 460 kw. supplied to the 10,000-volt line feeding the pumping stations.

Assuming that it is necessary to run this system an average of 200 days a year, 24 hours a day, the installation will consume 2,208,000 kw-hr. To an installation of this size it may be assumed that power can be supplied from a water power plant at not more than 1.5 cents per kw-hr., making a total cost for 10,000 acres (4,046 hectares) of land $34,000 per annum, for power, or $34.00 per acre (0.4 hectare) per annum for the 10,000 acres (4,046 hectares). Taking into consideration the climate existing in this locality and the soil which this water will supply, this is an extremely reasonable irrigation power charge.

The actual method by which the charge for power will be made to this particular pumping circuit, however, is that there will be charged against this section of land a sum representing the cost of the final development of power set aside to supply this pumping system for the Indian Department when it is all completed, and this pumping area will then pay the actual cost of furnishing such power. This will reduce the power cost to about one-third of that estimated above. So far as depreciation, renewals, repairs and attendance is concerned, it without doubt will compare well with any system of its kind heretofore constructed. The wells themselves are of a character which will probably last indefinitely. The equipment is one which it is believed will present a minimum of repairs.

Under the above assumption of operation, there will be 24,000 acre-feet of water lifted an average of 50 ft. (15.2 m.) at a cost for power of $34,000, or at a cost of $1.42 per acre-foot, making $0.0285 the cost per acre-foot one foot high, which is the figure upon which comparison should be made with other installations as to power cost.

In regard to the Salt River Project, it is expected that there may be constructed over 100 pumping plants similar to these de-

scribed in the Pima Indian Reservation. These will serve the purpose of drainage as well as add to the irrigated area. The power for these plants will be furnished, of course, at cost, as the operation of the pumping system will be a part of the project.

This brief description of these two installations, covering two types illustrating the subject under discussion, represents only a portion of the work of this character which is being carried on by the Reclamation Service. There are many complex and interesting problems connected with the various projects, for which there is no space in this paper.

A paper presented at the Pacific Coast Meeting of the American Institute of Electrical Engineers, Los Angeles, April 25, 1911.

TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT

BY R. J. C. WOOD

REQUIREMENTS

In order that a transmission system may satisfy the operating engineer it should fulfill the following conditions:

1. The requisite amount of power must be transmitted with reasonable voltage regulation.
2. Interruptions must be reduced to a minimum.
3. Flexibility of operation should be assured.
4. Ease of repair is essential.

REGULATION

The voltage to be used is chiefly, if not entirely, determined by economic conditions. It is as easy to operate with 60,000 volts as 15,000; indeed, there seem to be more short circuits and troubles on the lower voltage lines, probably because of the less careful construction used and the lesser absolute insulation margin allowed. We hear from the lines operating above 100,000 volts that they encounter no greater difficulties than do those of lesser potentials.

Up to distances of about 150 miles (241 km.) frequency is not a very vital matter. An increase in voltage will offset the difference in regulation between 25 and 50 or 60 cycles. This factor will be decided by the relative importance of the classes of load demanding either high or low periodicity, so as to make the total cost a minimum, and the consumers' satisfaction a maximum.

There are various formulas for calculating regulation, and it

is not necessary to refer to them in detail, beyond remarking that the conditions surrounding the delivery of power are often somewhat indeterminate. The power factor of the load, for instance, is often not to be foreseen between wide limits. This uncertainty renders abortive any extreme accuracy of method as applied to calculating the line.

It will be immaterial, therefore, when considering moderate distances up to 150 miles (241 km.), whether a formula is used, based upon the capacity being all at the center, part at the ends, or uniformly distributed over the line.

The allowable drop of voltage will depend upon conditions. Where power is transmitted in a block from the point of generation to a center of distribution, the regulation may be as high as 25 per cent. In such a case the voltage drop will probably be limited by the value of the lost power rather than by any operating difficulties.

The nature of the load will also bear upon the allowable voltage fluctuations. A mixed light and power load will demand closer regulation than either class of load by itself. If the service is all power a certain unsteadiness of voltage is allowable and if it is all light the changes in load will come on in such a manner that the operator can follow them by hand regulation.

When, however, the transmission line is part of an interconnected network and may have to transmit in either direction, then the regulation must be low in order to keep within the range of the regulating devices used in substations. If, for instance, a hydroelectric and a steam plant are at opposite ends of the line and there are numerous substations between the two, the flow of power may be either way.

Most probably the important center of distribution will be where the steam plant is located, and the voltage must be kept uniform at this end. The voltage at substations along the line will then vary by an amount equal to double the regulation of the line.

This fluctuation can be entirely eliminated from the distributing circuits by using automatic regulators, but the main transmission line should only have one-half the regulation that would be permissible were it a straight one-way transmission.

In loop or ring systems, fed from both ends, the circuit must be heavy enough to permit of feeding the entire load, all around the loop, from either end. If this is not the case it will be found that when certain sections of line have to be cut out for inspec-

tion or repairs, the open end of the loop does not get satisfactory service.

The amount of power that should be carried on a single circuit bears a relation to the total power of the system, the importance of certain loads, and the balance that the management draws between insurance against loss of revenue and prestige, and investment costs.

It will probably be wise in systems of 60,000 volts and above to confine the capacity of each circuit to 100 amperes. Baum has shown that the surge voltage, due to sudden interruption, is equal to 200 times the amperes, so that in the above case there would be a rise of 40,000 volts when a circuit breaker went out, supposing it to be open at double normal current. This would give a total voltage of 100,000 when superimposed upon a 60,000-volt line. Line and transformer insulation would stand this momentarily.

In order to deliver uniform voltage to the consumer, a variety of automatic and non-automatic devices are in use. It is questionable whether automatic regulation is desirable at the generating station, unless a type of regulator is used that will discriminate between the drop of voltage, due to increasing load, the drop occasioned by extreme overload, and that due to short circuit.

There are these three conditions to be met. Regulation for variation of load is comparatively simple, but when, due to troubles on the line, certain generating plants get left with more than their share of the load, we need a regulator that will discriminate and lower the voltage to a point where the generators will carry a safe current. Again, if a dead short circuit occurs on the line, the regulator must automatically lower the voltage as much as possible so that the arc may break; it should also, as soon as the line clears up, proceed to slowly build up the voltage to normal. It is too much, perhaps, to ask all this of an inanimate device, besides which it might deprive the switchboard operator of his job.

If synchronous apparatus is in use at the receiving end of the line, an automatic regulator controlling its field is quite feasible and should give excellent results. It entails, however, the fixed charges upon a considerable investment and certain operating expenses. Distributing feeders from substations along the line can be automatically regulated by the various types of induction regulators.

Reliability

Second only to the ability to transmit with reasonable voltage drop is freedom from interruption. To insure continuous operation we must have first class mechanical construction in line and substations. In designing the line we may take the worst climatic conditions on record over at least 30 years and then allow a factor of safety of $2\frac{1}{2}$. This would give a limiting unit tensile stress of 22,000 lb. for copper and steel, and 10,000 lb. for aluminum. Compressive stresses in towers to be reduced by column formulas. The tower should in any case be strong enough to stand the unbalanced stresses produced by the failure of one conductor.

The stress upon pin type insulators may be limited by designing the tie wires to break at the unbalanced stress above mentioned. It is better in case of some catastrophe to a tower, or line, to have the conductors break the ties, then to pull over a succession of towers. To attempt to design a tower that will stand the total breaking stress of all the conductors, leads to economic impossibilities. The transmission should preferably be on a private right of way which should be cleared of trees and brush.

With sufficient spacing of conductors from each other and from the tower structure itself, and with insulators tested to $3\frac{1}{2}$ times the voltage to neutral for grounded Y, and $3\frac{1}{2}$ times line voltage for ungrounded delta systems, there should be no interruptions except those caused by lightning or malicious interference.

The requisite clearance between conductors and tower structure is sometimes underestimated; in certain parts of the country large birds will roost upon the tower. If the insulator is of the pin type they consider it a most excellent device to get under. All goes well until about 4 a.m. in summer time, when the bird wakes up, stretches, and grounds the line. The suspension insulator should be free from this trouble, provided there is enough space between the conductor and the cross arm below it.

To minimize lightning troubles all kinds of arresters have been used as well as ground wires. Ground wires seem to do no harm and in many cases have without doubt prevented trouble. They give an added stiffness to the line mechanically, and are a wise precaution to install in sections habitually subject to storms. So far no arrester is perfect, most or all of them will burn up at times, even the electrolytic type is at times untrustworthy

upon delta-connected high-potential systems. The only consolation the operator derives, when his arresters burn up, is the thought that perhaps they saved something more valuable. The most robust type is the horn gap, it needs lots of space to accommodate the power arc that follows a discharge, and it usually shuts the system down when it goes off, but other types sometimes do the same.

It may become necessary to put in, say, electrolytic arresters to take care of the surges, due to switching and minor climatic disturbances, and then protect these arresters with horn gaps, if this be possible, to take the irresistible discharges from heavy lightning, which would cause temporary interruption in any case. When lightning causes a disturbance on the line, the surge will usually not travel far, but will break over an insulator, the arc formed will in many cases break the insulator, due to the intense heat. Ring guards at top and bottom of the insulator have given excellent protection to the insulator, by carrying the arc away from its immediate neighborhood.

The choice of supporting structures will generally lie between steel towers and steel or concrete poles. From some preliminary estimates that have been made it would appear that reinforced concrete poles for long span work will be extremely costly.

Where the districts fed from the line are scattered over considerable territory the transmission will have to be laid out either on a radial or loop system. The loop or ring system has the advantage of giving each substation a source of supply over entirely different routes, which are not both liable to be out of commission at the same time.

If the loop is double circuited throughout, the substations may be divided between the two circuits. Normally, the loop will be open at about its center, being fed from both ends. In case of trouble the circuit breakers at the feeding ends will open up and cut out only about one-fourth of the stations connected. These stations will at once switch over to the good line. The opening in the loop will only be closed under emergency conditions.

The radial system necessitates double circuits on all branches if full protection is to be afforded, and for the same insurance against interruption is more costly than the loop arrangement.

As already incidentally mentioned it will be necessary to have relays and circuit breakers installed upon branch circuits so as to isolate trouble. There does not seem to be any reliable way to automatically cut out the faulty line when one of two circuits,

in parallel at both ends, becomes short circuited or grounded. We have had some success when generating at both ends of a two-circuit line. With the inverse time type of relays the faulty line has been cut out automatically at both ends in a great many cases. If generating at one end only then both lines will go out. We need very badly a reliable reverse current relay that will operate at zero voltage.

Any growing system will suffer sooner or later from an inadequacy in its switching devices. Switches that operated perfectly when the total generating capacity was small, will fail more and more frequently to handle the short circuit as the total kilowatt capacity increases.

It will be found that there is no room for the larger switches that should replace the original installation. It is almost impossible to have too much space in the switch galleries and bus bar compartments, and economy of space here, while it may have been attractive and looked all right when the plant was young, is all the same a false economy. The lack of a few extra feet between switches might lead to an entirely new lay out being required in a few years. It is becoming the practice to install additional reactances in generator circuits to limit the short circuit current of large systems. It seems a pity to have to do this and spoil the regulation of the machines to the point where auxiliary automatic regulating devices are essential. It is a question whether such immense systems should not be normally cut apart into sections of perhaps 50,000 kw. capacity. This would simplify operation and localize trouble.

Even in smaller systems, normally operating as a unit, it is necessary to have points where they can be instantly cut apart, leaving certain loads on certain generating stations. This is the operator's first move when short circuits occur; to separate the several sections so that the greater part of the system may suffer as short a time as possible. If all important transmission lines were built with at least three circuits then they would be self clearing, using only inverse time relays at both ends. It is, however, often difficult to get the money to build three lines where two will apparently suffice.

Too much complication in providing for all imaginable combinations of switching is to be avoided as defeating its own object, which should be to keep the customer supplied with energy as continuously as possible. When the operator has to stop and figure out what to do next in cases of trouble, precious moments

are being lost. To insure prompt operation a good telephone line is a necessity and the money will be well spent in building an independent pole line for its use. A telephone line running upon the same towers with the transmission lines is very likely to be inoperative just when it is most needed.

It is perhaps possible to formulate a set of rules, so that each station in a network knows exactly what to do under all conditions, but a word from the load dispatcher is worth many rules in the book.

Repairs

There should be sufficient circuits and switching facilities so that all sections of the line may be cut out for inspection or repairs. It is an added precaution to have ground clips on all line disconnecting switches, so that when a line is killed with the object of working upon it, it is also grounded at both ends.

Long transmission lines should be sectionalized so that is never necessary to cut out more than a fraction of the line at any one time. By having switching stations a convenient distance apart they also serve as resting places for the patrolmen. Circuits should also be so arranged upon the towers or poles that men may work upon it without getting into dangerous proximity to the other circuits which will be alive.

Conclusions

All the foregoing requirements are summed up in what might be as good a motto for the operating engineer as for the system he operates, namely: capability, reliability, flexibility and repairability.

DISCUSSION ON "TRANSMISSION APPLIED TO IRRIGATION", AND "TRANSMISSION SYSTEMS FROM THE OPERATING STANDPOINT." LOS ANGELES, CAL., APRIL 25, 1911.

A. H. Babcock: Mr. Woods' paper is practical because it is based on real experience. For some years it has been my opinion that if more such experiences were put on record much good would result.

The author states that for distances up to 150 miles it is immaterial whether the capacity is taken as being all at the center, part at the ends, or uniformly distributed. Perhaps he will be willing to give his opinion where the line must be drawn, *i.e.*, what is the limiting distance where one's assumptions should change.

It is also stated that the tower should be designed for the unbalanced strains produced by the failure of any conductor. Is it not usual that when one line fails it takes another with it? It seems to me that it is necessary to go a little further and to provide for simultaneous failure of at least two conductors. Of course the financial conditions of the problem must determine in the end how far such insurance can go.

The author's remarks on switching must strike forcibly those who have been obliged to remodel switching and bus bar structures that have been found inadequate.

C. L. Cory: An interesting point brought out in a paper presented in San Francisco last May by Mr. Hays on the irrigation system developed in the San Joaquin Valley for the Mt. Whitney Power Co. was that in that plant certain economies resulted from not investing too much money in the beginning.

Wooden flumes were found in that particular installation to be quite satisfactory, and wooden pole lines gave good results. In the beginning the load was not heavy; and as the load increased, a reserve steam plant was installed down in the valley; and as an ultimate result the plant was a success. In other words, the duration of time necessary to get a load for this irrigation plant was such that it was not advisable to build a plant at first for all time.

The two plants described by Mr. Ensign and Mr. Gaylord, while for an entirely different class of service indicate that there are some circumstances where the character of work may even in our irrigation problems be permanent. I believe that the authors will agree with me that perhaps there are instances where this excellent construction would hardly be justified in the very beginning, as unquestionably was the case in the early days of the Mt. Whitney Power Company.

But when we see plants designed, laid out, and completely developed in every detail, such as the plant in Idaho and the one on the Salt River, we are impressed with the fact that irrigation and the use of electricity in pumping for irrigation, has come to about the same standard as the transmission plants for

metropolitan use for transportation and other purposes. I have had the pleasure of seeing the plant at Salt River, not all completed as described in the paper today, but there are a number of features about that plant that I recall. The tower line from Roosevelt into Mesa and Phoenix is a pleasure to see. There is a separate telephone line put up in a permanent manner—not upon wooden poles but upon inexpensive pipes or straight iron poles, and the entire construction is excellent.

There is one thing in making even a preliminary investigation of the installation of electrical plants for irrigation, which has to be constantly borne in mind. Mr. Ensign, as I remember it, said this morning that the capital charge against the land which would be irrigated from the Idaho plant was about $40 per acre.

Now, ordinarily when we build a large steam generating plant, or a transmission system which is used for transportation purposes, light, heat and domestic use, we do not necessarily have to consider the source of the money to pay for the income on the investment which ultimately takes care of all such charges, as depreciation and operating expenses. When we start to irrigate 200,000 acres of land, such as the Salt River project, including the storage reservoir, Roosevelt Dam, and canal system, and you see this land, as you might have seen it 10 or 15 years ago, you are impressed with the fact that the $40 per acre must come out of the productiveness of the land itself. In other words, it cannot come as an immediate result. The $40 per acre may possibly come in a few years, or it may require a number of years. In general, whether we have a gravity system of irrigation, or a large electrical installation, with the pumping plants and so on, the capital invested, the maintenance charges, cost of operation, and so on, will not be returned as rapidly as in many other installations of large plants. The investment is reasonably safe if the supply of water to be pumped is permanent and of the proper character, but there cannot be that immediate return, nor, I suppose, is it possible as quickly to load up the plant.

There is one point about which I would like to ask in regard to the first paper, and that is the period of the year or the annual load factor, if we might put it that way when electrical power would be used or needed for irrigation. To put it more definitely, I have in mind one location in New Mexico where it would not be necessary to pump water earlier than the latter part of February or the first of March. The summer rains come along in August, and it is only between March 1st and August 1st when the crops are starting that pumping is required. It is an important problem, under some circumstances, as to what we are going to do in irrigation projects with the power that may be generated at another period, or what are we going to do with our transmission plants of the character of the Idaho plant, if it is true that our irrigation is only needed five months out of twelve?

E. F. Scattergood: I wish to commend Mr. Ensign for having presented some cost figures in connection with the projects which he has taken time to describe. I do believe, further, that the time which we spend, as engineers, in writing descriptions of projects, and in reading descriptions written by others, is doubly valuable when accompanied by a statement of the features of construction and operation that have proved good and also of those that have proved unsatisfactory. We do not always hear about the bad ones, as we should and we should always be given the costs.

I remember very well my early experience with the Los Angeles Aqueduct work in planning for power for construction. I looked here and there and probably overlooked, but found very little of any benefit to an engineer wanting to know how much power is required, in a general way in construction work of that character; in what way to apply it and something as to costs. It seems that power is one of a number of such items that are usually allowed for by a sufficient percentage in estimates and paid but little attention while constructing such works resulting in an unnecessarily large total cost. After the first two years of aqueduct work I made careful summaries of the results as to the amounts of power required; the best methods of applying it; its bearing as to economical tunnel and conduit construction; the actual costs of the power system and the power delivered and comparisons with what the costs would have been if supplied by other methods. This was done for my personal use but when completed it was given to the Institute as published last August with the hope that it may be of benefit to others.

More such frank statements as those by Mr. Ensign would mean better team work and much greater accomplishment with an incidental betterment in the standing of the profession and every man in it. I do not see any disadvantage in it. I do believe that sometimes it might do perhaps some little harm, but I do believe there has been more harm done through ignorance of costs on the part of the public, than there ever would have been done through a proper knowledge of costs. There has unquestionably been great harm done, at times, through ignorance as to costs and in far more instances even greater injustice and wrong committed by taking advantage of such ignorance. I would like to know from Mr. Ensign whether or not the department would be free to develop power not needed for pumping purposes, and sell it, in order to make the results of the irrigation project more favorable to the farmer?

Paul M. Downing: In looking over Mr. Wood's paper, I find that his experience along different lines is very much the same as my own. He states that he does not consider any type of automatic regulator as being satisfactory for controlling the voltage at the generating end of a long transmission line.

This is particularly true of a large net work supplied from a number of different sources. On a system of this kind there are

a great many conditions coming up which affect the power house regulation. The character of the load may vary through a wide range during the 24 hours. The voltage regulation of one generating station will be dependent not only on the load carried from that station, but on the load carried from every other generating station, etc.

The conditions are entirely different from those obtaining where you have a single generating station and no inter-connected net work of lines.

I cannot agree with him when he states that the first cost of a synchronous condenser is a strong argument against its use. On the contrary, I think that very often it is an economical way of increasing the amount of power which can be delivered over a line.

On any long, high voltage line you almost invariably have a low power factor due to the induction motor load. This, together with the inductive drop in the line, gives poor line regulation. The use of a synchronous condenser enables you to raise the power factor to more nearly unity, but gives a most satisfactory means of regulating the line voltage.

The lightning arrester trouble to which he refers is something I think we have all had more or less experience with. Fortunately here in California there is little use for lightning arresters except in the higher altitudes.

Our greatest trouble, particularly in the Bay Districts, is from poles burning due to leakage over the insulators. Where you have one case of lightning trouble you will have a dozen cases of trouble from poles burning. This condition is generally the worst about the time of the first rains when the insulators are covered with the summer's accumulation of dust before they are washed by the winter's rains, and sometimes even two and three times during the summer and fall, to prevent this burning. After the first heavy rain little if any trouble of this kind is had.

J. A. Lighthipe: One of the points that was brought out by Mr. Wood's paper very strongly is that those who build a power system have no idea of what it will grow to be. The northern part of this State is practically under one system.

In Santa Anna we started with 33,000 volts, and 3000 kilowatts, and we were wondering what we would do with all that power. The whole line is now running in the opposite direction. The section surrounding Redlands is using about 10,000 kilowatts, and it is an open question whether we won't pump a great deal more to that end of the valley before many years.

The whole question of laying out stations and lines is a matter of prophesy. We don't know what we are going to run into in a few years. Fifteen thousand volts seemed to be almost the limit up to a few years ago. The first step to 30,000 simply staggered all the manufacturing companies. I can remember Dr. Bell publishing papers in which he stated that 40,000 was the limit that we could go; and we could not possibly

run beyond that. Now 60,000 is a common proposition. It is an open question whether we won't creep up to 100,000 or a 150,000, and we will have to if we increase our distances and areas of distribution.

Ralph Bennett: Mr. Lighthipe has mentioned the increase in voltage in recent years. We have now been operating in the Bay district for some time with 100,000 volts, and we have no more trouble with it than Mr. Downing had with 60,000 volts. In fact most of our trouble has been acquired from the 60,000 volt circuits which we feed.

A question has been raised as to the proper strength of towers. It is true there are times when several wires fail, but it is also true that there are usually additional circuits on the tower wires which will not fail and which will aid it in standing. Our suspension insulators are good for 15,000 lb.

After a flash-over, due to fog on the insulator, or lightning trouble, we can at once resume service. It is not like the old condition with wooden poles and wooden arms, where when we burned the pole head off we had to send a crew out to fix it up.

C. W. Koiner: Messrs. Ensign and Gaylord's paper on Transmission should be of very great interest to all companies operating in the West.

Power for irrigation is now furnished on a great many transmission systems throughout the southwest. It should be profitable for the reason that this load can be taken on the off-peak. The paper is full of valuable detail cost, and it is apparent that a fair price can be received for power.

The construction cost when compared with similar cost of work elsewhere, is very low. This same thing applies to Table 2.

The capital cost allowable per acre for irrigation depends entirely upon what the returns are per acre. It should be remembered that to rehabilitate the old eastern farms and plantations in the South, we are called upon to put back in the soil from $15 to $30 per acre, and sometimes $40. If it costs $40 per acre to irrigate virgin soil in the west, this should not be high, when we compare it with our old eastern farms, and they are beginning to return increased profit on the cost of rehabilitating. It would be interesting to know to what extent power is used for heating from the Idaho plant in the winter.

L. J. Corbett: Mr. Cory raised the question of the length of time that the power was used for irrigation. Up where we are we have even a shorter season than he seems to think is profitable. Some of the contracts I have been instrumental in getting on propositions of that kind from power companies have been as low as three months. One hundred days is the usual irrigation season, and sometimes, for safety, we stretch it from the 15th of May to the 15th of September, making it four months.

A question, which was hardly an electrical one, but more of an irrigation question, that was interesting, was the idea of using the surface waters and preventing them from rising beyond a

certain level and reducing them by taking them off and using them elsewhere for irrigation. That was a difficulty in the early days, in the Yakima region, and a great many people used it as an argument against irrigation, saying that it spoiled the land, making it sour, and that after a few years the land was ruined; but with the methods that are being developed now and the studies being made, such damage will be prevented.

Around Spokane there is a very interesting condition. The Spokane Valley is all underlaid with gravel. There are deep gravel beds ranging from 50 to 150 and even 250 feet deep. We have not gone to the bottom of them, but there is a water sheet there that certainly contains more water than the Spokane River, that travels right down through the valley. There is coarse gravel at most places at the water level, but there is such a flow going through that if you drop chips or sawdust on one side of a well, it is but a little time until it goes to the other side in the direction in which the river is flowing. To show what a heavy flow there is I would say that from wells eight feet in diameter, large centrifugal and turbine pumps are pumping as much as 5000 gal. a min. without visibly lowering them. When the pump is first started the water level falls from a foot to a foot and a half, where it remains constant. It pours right in from the sides. It is just like pumping out of a lake. The land the water is applied to is a black gravel soil and there is no danger at all of souring that land. The water is never left on the surface except in some cases in the winter when the ground is frozen and the melting of the snow leaves pools. It is well drained naturally. They are putting in wells there and buying power from the power companies.

In the discussion it was brought up by one of the members that irrigation came on the off-peak period. There are two companies furnishing power there, and one company, which has had a railroad and lighting load offered a special contract at reduced rates, if the irrigators would keep off their peak, which was from five in the evening until 11 o'clock at night; but in this particular place in the valley, tracts were being sold to parties living in and around Spokane, and many of the purchasers were working in Spokane and would come out there in the evening to take care of their suburban homes. Also the evening was considered the best time to irrigate and in this case that contract was refused and a higher rate paid in order to be at liberty to irrigate at any time.

R. W. Sorenson: I believe a good many of the companies have adopted the practice in calculating transmission lines for high tension of limiting the capacity in one line to about 20,000 kilowatts. In the paper given by Mr. Wood he stated he would limit the current capacity of a line to 100 amperes. This, of course, means in general that the capacity of any one line is limited to a quantity considerably less than the 20,000 kilowatts frequently used, as only a comparatively small number of lines are operating at a potential of 120,000 volts.

I believe Mr. Wood stated that they used a factor of safety sufficient to allow for the falling of one wire. Is that on a single line, three-phase transmission. Does Mr. Wood allow more strength on a system which has two lines?

A point which is of interest to me in connection with the paper on irrigation prepared by Mr. Ensign, is, can any man pump under his property to keep the water level down and thus keep his own land from souring, or even use the water for irrigation? Can any man drill a well on his property and work on that basis? That may be a familiar question to a lot of people in this section but I am not familiar with anything covering that point.

J. H. Lighthipe: That question has been in the courts of San Bernardino County for ten years. They have dropped salt in one well and used chloride of silver tests half a mile below and injunctions have been placed on well after well. A man there would have a well flowing from 200 to 300 inches of water. They kept digging well after well, soon these would stop flowing and pumping had to be resorted to. Later he would have to go down twelve or fourteen feet. They went so low in one district that in some places the pumps are down in the holes 40 feet. The question of the ownership of subterranean water has been in the courts of San Bernardino county for a great many years, and it is in the courts there today. I don't think it has ever been settled.

Ralph D. Mershon: This paper states that greater trouble is had with low voltages than with high ones. Where such is the case, I do not understand why it should be, unless for the reason stated by the writer of the paper that the engineers have been so used to considering 15,000 volts a low voltage, in connection with which so little care is necessary, that they have not taken the requisite amount of care in the installation of it. In this connection I may say, it seems to me that in some cases high voltages are used where their use is not properly indicated. The design and installation of a high voltage transmission plant is an interesting piece of engineering work, but the adoption of a high voltage for this reason is not, to my mind, engineering. True engineering is based upon economics, and does not indicate the use of a high voltage except where it is economically justified. The object of using a high voltage, rather than a low, is, or should be, to save money. That is, to accomplish by the use of the high voltage something which can not be accomplished otherwise, except at greater expense. But it is certainly not economy, nor, from my point of view, true engineering, to adopt a high voltage, when, for instance, the saving in line copper by its adoption is more than offset by the increase in cost of insulators and transformers. In some cases where a high voltage has been adopted it would appear that economic considerations had not had any part in the decision to adopt it.

These considerations are of special importance in the case of some of the transmission systems in this country, which, instead

of being transmission systems pure and simple, are really high voltage distributing systems feeding a very considerable number of comparatively small customers. In such cases it may be much better to adopt a lower line voltage, with a higher cost of line conductor, in order to enable the system to serve small customers, that, at a higher voltage could not be profitably served because of the prohibitive cost of step-down transformers and controlling apparatus.

Referring to the question of lightning arresters. Very good success has been had in the eastern part of this country, and in many places abroad, with the horn type of arresters with graded gaps. That is, from two to four gaps on the same circuit, the gaps being of graded dimensions, the smallest gap having in series with it a high resistance, the larger gaps lower resistances, and the largest gap a fuse.

I can heartily recommend a careful study of the paper read by Professor Creighton at the recent Schenectady meeting of the Institute, which has to do with taking care of arcs to ground; and in connection with that paper the remarks made by Mr. L. C. Nicholson, and a previous paper by Mr. Nicholson relative to a method of protecting pin type insulators against the effects of arcs. The results obtained by Professor Creighton are very interesting, and Mr. Nicholson, who had previously been working along the same lines for over a year, has obtained, on the system of the Niagara, Lockport & Ontario Power Company, results even more remarkable than those reported by Professor Creighton.

There is a question I would like to ask Mr. Ensign. I appreciate that it cannot be answered definitely, but possibly he can answer in a general sort of a way. I should like to know from what depth he has found water can be profitably pumped for irrigation in this part of the country. Another question I would like to ask is as to the total depth of water required in irrigation in this part of the country.

Bearing on the point Professor Sorenson mentioned, the matter of unlimited pumping on your own land has arisen in the Transvaal, especially in the neighborhood of the Vaal River. As I understand it, there are at the present time laws in the Transvaal which prohibit the unlimited pumping of underground waters, because of the fact that by so doing you may rob your neighbor of the water under his land and required by him for irrigation purposes.

I do not entirely agree with Mr. Wood's statement that grounding the neutral of a three-phase system through a resistance results in an indefinite condition as regards the voltage to which the transmission line may be subjected. The voltage will be definite if the proper value be chosen for the neutral resistance. If the resistance be made too high there will be danger of oscillatory effects. But it is possible to adjust the resistance to a low enough value to avoid oscillatory effects, and at the same

time sufficiently limit the amount of current which can flow through the neutral. With such an adjustment the maximum voltage that can occur between a line conductor and the ground is something less than that which normally exists between the line conductors.

In the case of the system I have mentioned, that of the Niagara Lockport & Ontario Power Company, the neutral resistance has been chosen low enough to remove the possibility of danger of abnormal voltage, and yet high enough so that when the arc strikes from the cable, or its protecting metal, to the guard ring it will attenuate and go out, of itself, unless, due to wind, or some other condition, it elongates enough to produce a short circuit between line conductors, in which case the automatic mechanism, provided by Mr. Nicholson at the station, operates and extinguishes the arc.

O. H. Ensign: I want to answer a question that someone has raised, Mr. Cory, I believe, about the permanency of the work shown in my paper, in connection with Mr. Lighthipe's experience. It would have been better for Mr. Lighthipe to have had a concrete caisson with pump suspended from the top. Much of the history of the southwest shows a lack of foresight in doing the work in the first instance so as to anticipate conditions one could not forsee because of the short period of experience with the physical conditions of the country. The form of plant described in the paper can not be put out of commission by any probable variation of the water plane.

There are a number of pumping stations where this same thing has occurred, where they have followed the water plane down as the water plane sunk, and got their pumping plant down and could not get it out or use it when the water returned. Having had that in mind, and having had a great deal to do with the development of underground water before I entered the Reclamation Service, we were able to take advantage of that experience in the first plant for which we were responsible. This was the Pima Indian Reservation, which is described in the paper. In this type, you have a well that will last indefinitely. If your water plane does fall, you can still go on further until you reach the point which has been questioned as to the practical depth at which you can lift water for irrigation. That is a question of the nature of the crop and the time and amount of the rainfall that you have in any location.

I have mentioned in the paper that in this valley, Southern California, water is apparently lifted 200 ft. successfully for oranges. I want to qualify that, because the successful growing of oranges is a very indefinite term. A great deal of money is made by a great many people who know how. I honestly believe that you can afford to lift water with economical apparatus something over 100 ft. after you have acquired the grove and it has become a producing property. For the growing of alfalfa I question whether it is profitable to raise water over 30 ft. in

small plants even where we can cut six crops per annum, as we do at Yuma and Salt River and some other places. All these things vary, and every community has its own economical points which have to be watched before one goes too far, and it is a very broad and indefinite problem.

The question as to the right to pump underground waters. I believe, that the courts have said in Southern California that you can pump on your own land almost in every case, provided you do not send it off on to somebody else's land and sell it. I believe that is the interpretation of the law. Somebody had better correct me if I am not right on that. But it has been decided that you cannot develop water and transmit it for a general irrigation system in Southern California when that injures prior right. I am not up in law, but that is my memory of one or two cases that have come to my notice.

In the first part of the discussion, the question was asked what to do with the power in the non-irrigation season. That almost solves itself. In the first place, most of the reclamation power plants, Minidoka being an exception, however, are derived from the water which is used for irrigation; that is, the water has been or is being diverted. If it has been stored, it is let out only as needed during the irrigation season, (or it was not worth while to build the dam), and the power so developed of course is used at the same time as it is then wanted for pumping for irrigation, and the two needs exist together and work together as one problem, and in many cases there is no winter pumping to be done at all. It may occur again that there are other power plants on the project for instance, the Salt River Valley Water Users Association have agreed to put up a certain sum of money to build on that project certain power plants, which are made possible by the irrigation works, and with the idea of using them for revenue from the sale of power. The Roosevelt plant was built primarily as a pumping power plant only, although there was existing in the Valley a contract with one of the old irrigation companies with the electric light company in Phoenix, which had to be taken care of, and it has 20 years yet to run. The Reclamation Service is now selling them power from the Roosevelt Dam, but this will be shut off when water is not needed from the dam as soon as these other plants in the valley are built, which are now under contract, and they will use the natural flow of the Verde River and the irrigation water which flows through the canals and are to be located on drops in the canals. Ultimately there may be developed something like 8,000 h.p. besides the power of the Roosevelt Dam.

Something has been said of the capital cost. The capital cost of the Minidoka plant is about $18 per acre so far as the actual power plant, transmission lines and pumping stations, are concerned. The $40 which I mentioned (and which has not been announced as such, but is somewhere in that neighborhood), is the cost of that portion of the project interest in the dam

which diverted the water in the first place, and the cost of power and pumping, distributing systems, turn-outs, and all other parts of the system.

Now, there are a number of projects in the United States built by private corporations, and some by the Reclamation Service, in which gravity systems have cost more than that.

Ralph D. Mershon: In figuring these costs, do they include the interest on money during the construction of the dam?

O. H. Ensign: The Reclamation Service is financed by the money received from the sale of government lands, and is loaned without interest to the people who are to pay for it ultimately, the Reclamation Service acting as a trustee, as it were, using this fund, building these works which the people pay for in ten annual payments after the works are finally completed and the cost is known. So the interest is not charged into this cost. They pay no interest on the money whatever. It is mentioned in the paper that there is no interest charge on the money.

The primary idea of the irrigation law was to bring into some degree of value many areas in the west which were beyond the reach of private capital—that is, to irrigate them. I do not believe you could have interested any banker in any sort of irrigation securities in 1902 and 1903. I have heard it stated on reliable authority, and I believe it is true, that up to 1902-3, no private irrigation corporation had ever paid interest on its bonds. That may not be exactly so, but it is nearly so. Very few of them were successful from the standpoint of the investor. The primary cause of that was lack of knowledge of the run-off of the various watersheds in a new country and a lack of interest in the promoter in making sure what that run-off was, and an effort in almost every case to cover more land than the run-off would take care of. They incurred expenses to deliver water, made contracts for water, and sometimes a rather wild finance scheme was attached to the plan, and left the irrigator with a chance to reclaim a portion of the area contemplated if he took hold of the property on the basis of his riparian rights to take care of himself and build it, as in many cases has been done. But the man who put his money into it as an enterprise from which he expected to get revenue, I might say, nine times out of ten received nothing. And the irrigation law came out at that time with the idea of correcting that situation, of bringing together some of these into actual success.

The Salt River Valley presents the most startling fact in that connection. When the Reclamation Service went in to build the Roosevelt Dam, the Valley had been unsatisfactorially served by private corporations. The Salt River is a torrential stream, probably one of the most torrential in the country. I myself have seen it rise from 500 second-feet to 150,000 second-feet in a few hours. It is quite an undertaking for any private capital to build a dam on such a stream. Since the Service started to build that dam, enough water has passed the site to

fill it eight times. Just before President Roosevelt opened it, 250,000 acre-feet were stored in it in one day. Floods have passed which would have filled the reservoir in twenty-four hours, and it holds enough water to cover a strip a mile wide and a foot deep from San Francisco to Detroit, Michigan. That is about the best way I can give it to you so you will remember it. It contains 1,300,000 acre-feet.

The Reclamation Act provides that the Secretary of the Interior shall take the funds arising from the sale of public lands and use them for the creation of irrigation works. Practically the only restriction is that no man shall hold over 160 acres of land. If he can make a livelihood, or keep himself busy on less, he shall not have any more land than necessary to support him and his family profitably. In some places it is forty acres; in some places it is eighty acres; Minidoka is eighty; at Yuma there are some places where they think of dividing it up into twenty. The former has ten years to pay for the works in. After the work is complete and the costs are known, the cost is assessed to the land, and liquidated in ten annual payments, plus the actual cost of maintenance and operation during that period, paid by the farmer. In a case like the Salt River, where practically 90 per cent of the land was settled, the government places what amounts to a mortgage on the property to cover the cost before work is begun. There has been a great deal of talk about its being a land speculating scheme where there was no government land the land being already settled. In Salt River Valley they had made effort after effort to control that turbulent stream with continued loss to themselves. Therefore, it was more of a God-send than a speculating scheme that the Reclamation Service could take up the work in the Salt River Valley and make it one of the solidest communities in the whole West.

Coming to this question again of the sale of power, at the Minidoka project, we have an entirely different proposition than we do at Salt River, where we have no real right to generate power except for pumping purposes, except such surplus as may pass the Verde at flood stage or other run-off periods. At Minidoka we have to pass something like 3000 second-feet to the water rights below, during the irrigating season and the remainder of the time the minimum is about 5000 second-feet. In order to keep the operating force the year around and to reduce the all around yearly cost of pumping we are selling power at a very low rate to the several small towns which have sprung up on the project. We are selling this power to those towns at a very low rate in order to bring the towns into a better condition and in order to make them more agreeable places to live, as it is a pretty rugged country in the winter, although a very productive and delightful one in the summer. We hope to build the load up, and are today encouraged that we shall more than pay the operating expenses of the plant during the period it is not

operated for pumping. The irrigation season is possibly from the 15th of May until the 15th of October. We have started one season on the 15th of April. In order to get a load that was reasonable from the use of power in the communities, or small towns, we have undertaken to do some heating there. We are selling heating current at a price, I am almost ashamed to mention. But the people themselves, having built these plants with their own money and owning them, and having to stand behind the operation, the prices are not unreasonable. The prices for light and power are just about the same as the adjacent towns. We are selling power for heating at $1.25 a kilowatt a month at a flat rate.

As to the question of developing power and selling it, to reduce the operating cost of the project that has not been authorized. There was a bill passed Congress authorizing the Reclamation Service to sell power, or contract the rental of power sites, up to the limit of ten year contracts. We have under way several construction plants of from 1000 to 1500 kilowatts. They will be used in the construction of dams, and when finished they can be used for whatever purpose desired by the Water Users Association which has paid for these plants in paying for the other works. Undoubtedly there will be found a market for the power and in most cases it will be used largely for pumping.

One or two questions have been asked that I can best answer in a general way by the way we attempted to handle the irrigation pumping problems in this country in the early days of transmission. The first irrigation pumps were started on a 16-hr. basis. Some of them had the privilege at a higher rate of staying over the peak load provided they would cut off on telephone call. That is what is meant by the off-period that has been spoken of, that irrigation may be built up and the valley in the load curve built up and a profitable revenue from that source obtained. There has been one disappointing thing about it. Some seasons were wet seasons, and it would be necessary to shut off irrigation for a long time. In some seasons it diminished to one-half. It is not a load that can be entirely relied upon.

R. J. C. Wood: Mr. Babcock asked at what distance you should switch over from approximate formula to accurate formula in calculating transmission lines. There is no one particular distance where you leave one and get into the other, because they diverge from each other gradually. I would say that up to 150 miles you can use your approximate formula. After you get over that, you had better check it by the correct formula.

He also suggests that more than one conductor may go down at a time. Most of our experience has been that when we get in trouble on the line it is from one conductor to the tower, and it is not between wires; so the switchboard man up in the generating plant, as soon as trouble comes, at once shuts off the current and saves the other wire. The other wire is not involved; there is only one wire involved.

Mr. Downing agrees with me as to the automatic regulator at the generator end, and he states that it is cheaper to install synchronous apparatus than a lot of copper in the line. I believe that is so.

I said there were certain charges necessary more as a statement of fact than as an objection to the system of using synchronous apparatus.

In regard to limiting the capacity of circuits to 20,000 kilowatts or 100 amperes, I think it is the general opinion that it is the number of amperes you break in the switch which does the damage. Possibly basing the switch capacity on amperes is a little better than basing it on kilowats. Mr. Mershon says he was astounded at there being more trouble on low tension than high tension. It may be because there are more miles of the low tension wire that you get more trouble coming in through it, in addition to the fact that it is not built so carefully. I notice he got good results by having resistance series. I suppose you have got to hit the mean between running an ungrounded high tension and a high tension connected solid with the ground. If you are connected solid to the ground you limit your tension on one wire. Can't you put resistance between the neutral and ground? You don't know what you are going to get on that line. The neutral point will shift around and you may get all kinds of voltage, because if the resistance is low, that would indicate the resistance. If the resistance is too low, that will not bother your current. You have to know just what you want.

STICKERS FOR FLYLEAVES

OF PARTS I AND II

A. I. E. E. TRANSACTIONS, VOL. XXX.

A complete synoptical and topical index of this volume of the Transactions is printed at the end of part III.

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